CHAPTER 14

Magnetism

CHAPTER CONTENTS

Electromagnets come in all sizes. Large, powerful electromagnets are used in industry to move heavy materials. Tiny electromagnets are used to read and write the data on the disk drive of a microcomputer. While electromagnetism is a common phenomenon today, it was first discovered purely by accident in 1819. Until that date, electricity and magnetism were believed to be completely separate phenomena. Immediately recognized for its importance, the discovery of electromagnetism marked the birth of modern science and technology. Without an understanding of electromagnetism, devices such radios, televisions, computers, tape recorders, VCRs, CD players, lasers, electric motors, and generators, could not have been invented.

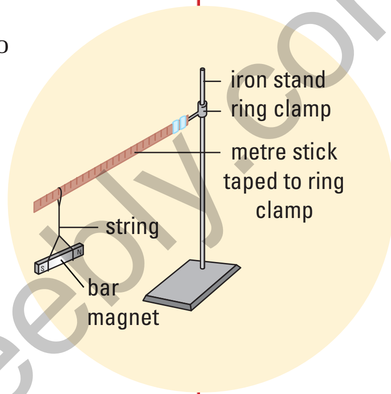
In this chapter, you will study the properties of natural magnetism and electromagnetism. You will investigate how electricity and magnetism are related. You will also learn how electromagnetism is used to create electromagnetic devices such as electromagnets, loudspeakers, motors, and meters.

MULTI LAB

Magnetic Interactions

Invisible Lines

Use a string to create a hanger for a bar magnet. Allow the magnet to hang freely, away from the influence of any other magnets or magnetic materials. Allow enough time for the magnetic to come to rest in the absence of vibrations or air currents.

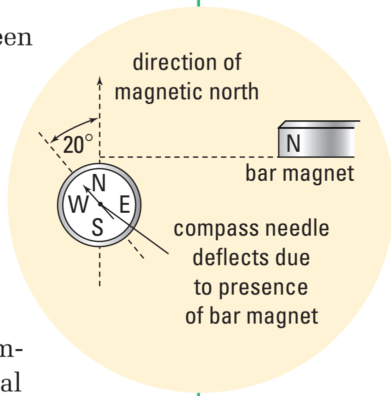


Analyze and Conclude

1. Note and record the orientation of the long axis of the magnet once the magnet has come to rest.
2. Compare the final direction of your magnet's rest position with the positions of your classmates' magnets.
3. Draw conclusions about the final orientation of the suspended bar magnet.

Magnets and Materials

In this activity, you will test the properties of magnetic forces between magnets in the presence of various materials using a sensitive magnetic compass. Place a compass on your desktop. Once the needle has come to rest, position the body of the compass so the 0˚ mark is under the N-pole of the compass needle. Place a bar magnet on a line perpendicular to the axis of the compass needle. Slowly move the bar magnet closer to the compass until it causes the compass needle to deviate about 20˚ from its original position. Place several different types of materials between the compass and the magnet. Carefully observe any change in the direction of the compass needle. Test the effect of changing the orientation of the material separating the compass and the magnet. Use a second bar magnet to determine which substances are magnetic and which ones are not. Organize your observations in a table. Possible substances to test: copper, zinc, aluminum, iron, lead, plastic, glass, wood



Analyze and Conclude

1. Did the presence of the material placed between the magnet and the compass affect the amount of deflection of the compass needle?
2. Did the orientation of the material placed between the magnet and the compass affect the amount of deflection of the compass needle?
3. Draw conclusions about the ability of different materials to affect the interaction between magnets (the bar magnet and the compass needle magnet)? How do you think this occurs?

14.1 Natural Magnetism

SECTION EXPECTATIONS

- Define and describe magnetism.
- Use a scientific model to explain and predict magnetism.

KEY TERMS

- north-seeking pole
- south-seeking pole
- magnetic dipole
- domain
- temporary magnetism
- permanent magnetism
- Curie point
- dipping needle
- magnetic dip
- magnetic declination
- isogonic lines

PHYSICS FILE

The first magnetic compass is believed to have been created about C.E. 1000 in China and was used to navigate across the vast regions of Central Asia. By the thirteenth century, the compass was being used in Europe to aid navigation on the ocean. Until the arrival of the compass in Europe, sailors had to stay within sight of land in order to navigate. The invention of the compass enabled sailors to leave the coast and venture out into the ocean knowing they could find their way back with the compass. This resulted in the great global explorations of the fifteenth and sixteenth centuries, including the discovery of the "New World".

Figure 14.1 This is a common enough sight that we usually take it for granted.

What is the mysterious force that enables some materials to attract others? The first descriptions of magnetism go back to over 500 years B.C.E. A Greek, named Thales, wrote about a rock that came from the town of Magnesia. Thales (624? – 547 B.C.E.) referred to it as the "magnetes lithos" (Greek for "Magnesian rock"). Eventually, rocks that displayed natural magnetism came to be known as lodestone. Chemical analysis has shown that lodestone gets its magnetic properties from the presence of an oxide of iron, Fe_3O_4, known today as magnetite or magnetic iron ore.

Magnetic Poles

When you were doing the Multi Lab on page 3, you probably realized that a compass needle is simply a small bar magnet which aligns itself on the north-south axis for the same reason as the suspended bar magnet. In the Northern Hemisphere, the presence of the North Star or Polaris, has always been a powerful symbol. Early observers assumed that the compass end was seeking the North Pole, hence the name **north-seeking pole** was given to the end of the magnet that seemed to always end up pointing in that direction. Similarly, the name **south-seeking pole** was given to the other end of the magnet. Gradually, these became known simply as the **North pole (N-pole)** and **South pole (S-pole)** of the magnet.

No matter how often you break a magnet into pieces, each piece is a complete magnet with an N-pole and an S-pole. Scientists assumed that you could do this until each piece had only one atom or molecule. This led scientists to believe that the individual atoms of a material must be magnets. Because magnets always seem to come with an N-pole paired with an S-pole, the bar magnet is often referred to as a **magnetic dipole**. The reason why magnetic poles always come in pairs will become clear when you study electromagnetism.

For early scientists, magnetism was a much easier field to study than static electricity. First, magnets did not discharge when touched and therefore were easier to manipulate. Second, magnetism had a very practical aspect in its direction-finding capabilities. For nations that were interested in exploration, the true nature of magnets was a very important topic.

The distance between magnets affects the strength of their interaction. This has been known since at least C.E. 1300. In 1785, Coulomb devised an experiment, for which he invented the torsion balance, to find the mathematical relationship between the separation and the force. He proved that the force of interaction between magnetic poles, attraction or repulsion, was inversely proportional to the square of the separation between them. Mathematically this is written as:

$$|\vec{F}| \propto \frac{1}{d^2}$$

$|\vec{F}|$ is the magnitude of the magnetic force between the poles and d is the distance between the poles.

This explains why the N-pole of a bar magnet can exert a net force of attraction or repulsion on another bar magnet. When two magnets approach each other, it is almost certain that one pair of poles is going to be closer together. It is the interaction between the two poles nearest each other that will dominate the interaction of the two magnets. Thus, if the poles nearest to each other are unlike poles, then the force you observe will be one of attraction.

RULES FOR MAGNETIC INTERACTIONS

1. Like poles repel each other.
2. Unlike poles attract each other.
3. The force of attraction varies inversely as the square of the distance between of the poles.

TRY THIS...

What happens if you break a magnet in half? Do you get a separate N-pole and S-pole? Take a bar magnet and stroke the side of a hacksaw blade several times in the same direction with one pole of the bar magnet. When you have made about 20 strokes, confirm that the blade has become magnetized by bringing its ends near the poles of a compass. Does a force of attraction between the blade and the poles of the compass prove it is magnetized? Explain.

Wrap the blade in a piece of cloth to protect your eyes and hands, and break the blade in half. (They are relatively easy to break.) In turn, hold the ends of each half of the blade near the magnet. Do you have two magnets, each with an N-pole and a S-pole, or are there now separate N- and S-poles?

Wrap one section of the blade in the napkin, and break it in half again. Test each of the new parts of the blade for magnetism.

History Link

A compass invented in China about C.E. 1000 consisted of a spoon made from lodestone that was placed on a bronze plate. The spoon represented the constellation Ursa Major (Big Dipper), with the handle end of the spoon representing Ursa Major pointing away from the North Star. Why did they make the base plate of bronze?

Magnetic Domains

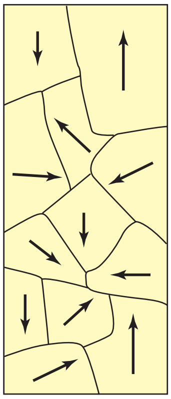


Figure 14.2 Because the magnetic domains are randomly oriented, the material displays no net magnetic polarity. (The arrows represent the magnetic polarity of the domains.)

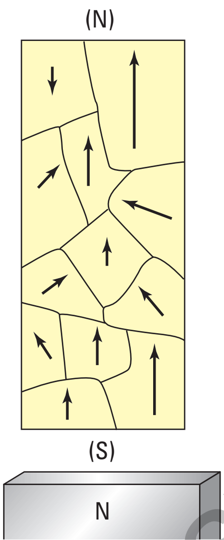


Figure 14.3 The external magnet has caused the orientation of the domains to shift so that they are in greater alignment with its polarity.

Imagine you have a box containing thousands of very tiny, very weak magnets. If you shake the box up, the magnets inside the box would tend to orient themselves randomly. A compass needle brought near the box might detect no appreciable net magnetic polarity for the box, even though you know it contains many magnets. Because the magnets inside the box are randomly oriented, more or less, the force of attraction from one magnet or group of magnets will be counteracted by the force of repulsion by other magnets or groups of magnets.

If you opened the box, what would you see? Probably there would be many regions, called **domains**, where a group of tiny magnets were lined up with each other, giving the domain a magnetic polarity (see Figure 14.2). Beside one domain, there might be another domain where the magnets, by chance, were aligned together but in a different orientation to the first domain. Interspersed throughout the box, there might be many domains of different sizes, strengths and orientations. In reality, the tiny magnets which make up the domains are actually the atoms or the molecules of the material.

Now imagine what would happen inside the box if an external magnet is brought near one end of the box. The pole of the external magnet that was near the box would exert a force on the domains and would try to align the domains. Even though the domains are not totally free to move, the force would shift domain orientations into greater alignment. In this way, the direction of the magnetic domains in the box would take on the same polarity in the same direction as the external magnet. The box is now a magnet that is attracted to the external magnet (see Figure 14.3). When the external magnet is removed, the domains would tend to sort themselves randomly again and the polarity of the box would become much weaker and even disappear completely.

In domain theory, the material is affected by the presence of a magnet if the atoms or molecules of the material are magnets. A domain is a group of adjacent atoms whose like poles have “like” orientation within the material. When the domains of a material are randomly oriented, the material shows no permanent magnetism. The presence of an external magnet can induce the domains to become aligned, more or less, with that of the external magnet. Thus, the material becomes a magnet in its own right.

In some magnetic materials, such as iron, the microscopic domains are easily reoriented in the direction parallel to an externally applied field. However, when the external magnet is removed, the domains return to their random orientations and the magnetism disappears. Thus, iron forms a **temporary magnet**. In other materials, such as steel, the internal domains are reoriented only with considerable difficulty. When the external magnet is removed, however random realignment of the domains is also difficult. Thus the material will retain its magnetic properties. These types of materials form **permanent magnets**.

Even though permanent magnets seem to be quite stable, they are fairly fragile. If a magnet is heated, its strength weakens but that strength will generally return when the magnet cools. However, if the magnet is heated above a certain temperature, called the **Curie point**, the magnet will be totally destroyed. Table 14.1 lists the Curie Point for several materials displaying permanent magnetism.

Table 14.1 Curie Points for Magnetic Materials

Material	Curie Point (°C)
iron	770
cobalt	1131
nickel	358
magnetite	620
gadolinium	16

The Magnet Earth

Prior to the sixteenth century, the reason why magnets aligned themselves to point toward the North Star had been a subject of great speculation. Some argued that there must be a huge mass of iron ore at the North Pole. Others suggested that Earth itself must be a magnet. An English scientist named William Gilbert put the argument to rest in 1600. Gilbert fashioned a lodestone into the shape of a sphere. After using a compass to locate the poles of his lodestone sphere, he decided that, since it attracted the N-pole of a compass, the magnetic pole in the Arctic region of Earth had to be a magnetic S-pole. The Antarctic region must contain a magnetic N-pole. A compass needle placed on the surface of Gilbert's lodestone sphere behaved like a compass on the surface of Earth.

Gilbert went one step further to prove his theory. Normally, a compass is held horizontally so that its needle rotates about a vertical axis. Gilbert built a compass that could pivot in the vertical plane about a horizontal axis. When this compass was brought near his lodestone sphere, it dipped toward the surface of the sphere. The closer it came to one pole or other of the sphere, the more it dipped (pointed toward the sphere's surface). At the lodestone sphere's equator, the needle of this compass was parallel to the surface. This type of compass is called a **dipping needle** (Figure 14.4) and measures **magnetic dip**. At the magnetic equator, the amount of dip is zero; at either magnetic pole, it is 90°. A dipping needle can be used to locate one's position with respect to the magnetic equator.

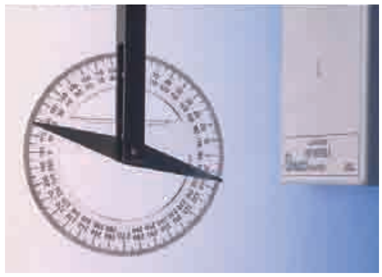


Figure 14.4 As the dipping needle is moved farther from the magnetic equator and closer to a magnetic pole, the amount of dip increases. At either magnetic pole, the dip is 90°.

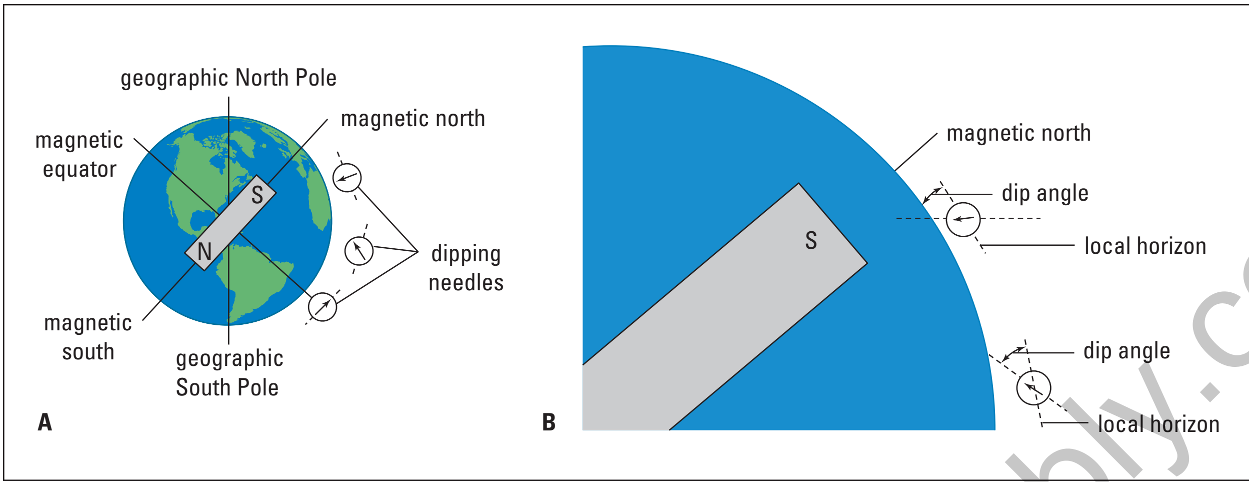


Figure 14.5 In 1600, Gilbert showed that Earth had the properties of a magnet.

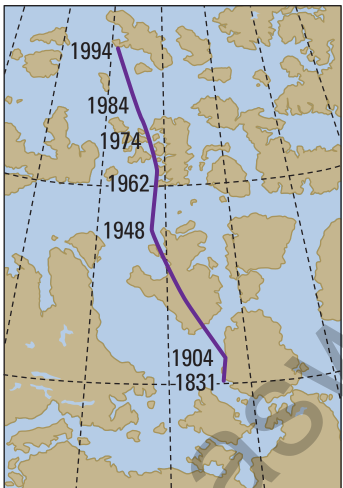


Figure 14.6 Earth's magnetic poles are not stationary. Since 1831, the magnetic North pole has moved steadily north and west. As a result, magnetic declination constantly changes.

Gilbert showed that on Earth, both compass needles and dipping needles (compasses designed to operate on a horizontal axis) would behave like the ones near his lodestone model of Earth. Gilbert argued that because the behaviour of magnetic compasses and dipping needles near his lodestone and Earth were sufficiently alike, it was correct to assume that Earth itself must be a giant spherical magnet.

Long before Gilbert's time, it was noticed that a compass did not point directly toward true geographic north. In 1580, in London, it had been recorded that a compass needle pointed 11° east of north. This is known as **magnetic declination**. In Gilbert's lifetime, the magnetic declination at London drifted from 11° east of north to 25° west of north.

Clearly, if the magnetic North and South poles were in exactly the same place as the geographic North and South Poles, the compass would always point in a "true" north-south direction and the declination would always be zero. Moreover, the fact that the magnetic declination changes indicates that the magnetic poles must be wandering somewhat. In 1831, James Clark Ross accompanied an expedition to the Canadian Arctic. There, he located the Earth's magnetic North pole on the west coast of the Boothia Peninsula in the Northwest Territories at a latitude of 70° north. When he stood there, the magnetic dip was 89°59'. Figure 14.6 shows its movement from that time to the present.

To use a magnetic compass effectively, you must be aware of the magnetic declination at your location on Earth. Detailed maps have been prepared that provide very accurate readings of the magnetic declination everywhere on Earth. The lines on these maps are called lines of constant magnetic declination or **isogonic** lines. Figure 14.7 shows the isogonic lines for a general map of Canada.

In many places on Earth, there are irregularities in the magnetic declination. At these locations, the actual direction of the isogonic lines deviates greatly from the direction that might be expected for that area. For example, north of Kingston, Ontario, the isogonic lines are 90° off the declinations for nearby locations. Anomalous angles of declination are accompanied by anomalous angles of dip.

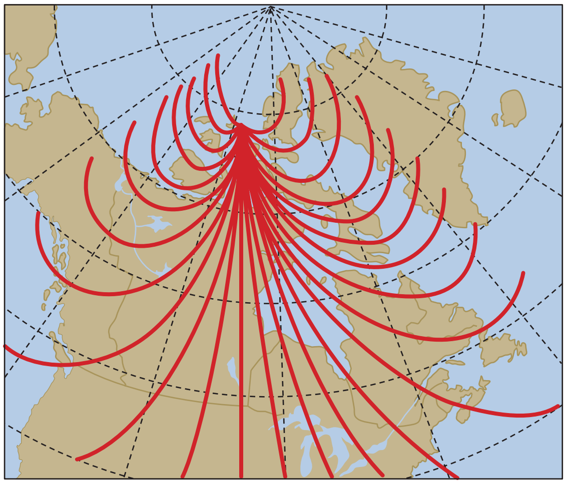


Figure 14.7 Maps that plot the isogonic lines enable navigation with a magnetic compass. Since magnetic poles are continually shifting, these maps need to be updated regularly. The Geological Survey of Canada (GSC) produces very detailed isogonic maps. In southern Canada, their maps achieve an accuracy of about 0.5°.

14.1 Section Review

1. **I** Imagine that you are given two iron rods that look identical. When you bring one set of ends together, they attract each other. However, when you reverse the end of one of the rods, they still attract each other. Obviously, one is a magnet and the other is not. Devise a test, using only the interactions of the two rods, to find out which one is the magnet and which one is the plain iron rod.

2. **C** It has been found that magnets can be destroyed by several different actions. One of these actions is to heat the magnet. As the temperature of the magnet rises, the magnet gets weaker. The temperature at which the magnet is totally destroyed is called the Curie point. Discovered by Pierre Curie in 1895, the Curie point varies according to the type of material. Use domain theory to explain (a) why heating a magnet weakens its strength and (b) what happens at the Curie point.

3. **K/U** If an iron bar is held in a north-south orientation and then is tapped gently with a hammer, it will become a weak magnet. In light of domain theory, why should this occur?

4. **K/U** If a steel knitting needle is stroked along its length by one pole of a magnet, repeatedly in the same direction, it will gradually become a permanent magnet. How can domain theory be used to explain this?

5. **I** Make a hypothesis to explain the cause of the local irregularities in the angles of declination for Earth's magnetic field? Do an Internet search to find information to support your hypothesis. Make sure that you consider the reliability of the source of the information. In your answer, include references to your information sources.

6. **C** Explain why it would be necessary to have a detailed map of isogonic lines if you wanted to go wilderness camping.

14.2 Magnetic Fields

SECTION EXPECTATIONS

- Demonstrate an understanding of magnetic fields.
- Describe the properties, including the three-dimensional nature, of magnet fields.
- Conduct experiments to identify the properties of magnetic fields.

KEY TERMS

- Action-at-a-distance
- magnetic field
- permeability
- magnetic lines of force
- magnetic dipole
- field density
- field strength
- ferromagnetism
- diamagnetism
- paramagnetism

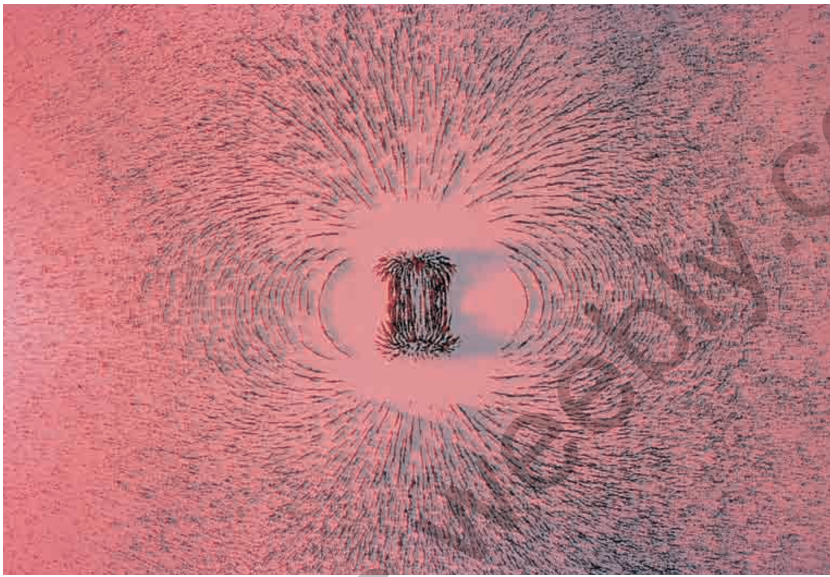


Figure 14.8 Iron filings reveal a two-dimensional picture of the magnetic lines of force.

One part of Newton's Theory of Gravity, published in 1687, was the concept of the **Action-at-a-distance** theory. Newton argued that somehow the sun acted-at-a-distance across space to pull Earth and the other planets towards it. Newton also proved that the force of gravity varied inversely as the square of the separation between the Sun and the planets. When Coulomb proved that the magnetic force, like the force of gravity, also varied inversely as the square of the separation of the magnets, it was not surprising that the Action-at-a-distance theory was applied readily to magnetism. Action-at-a-distance seemed to serve magnetism very well until Michael Faraday, while studying the patterns in iron filings that had been sprinkled around magnets, created what is known today as "Field theory".

Michael Faraday's concept of electric and magnetic fields revolutionized Physics. Faraday thought that the iron filings had formed the pattern around the magnet because they had been pushed by what he called magnetic lines of force. He observed that the **magnetic lines of force** exited the magnet at one end, passed through space, and re-entered the magnet at the other end.

According to Faraday, the magnetic force experienced by an object was exerted, not by the magnet at a distance, but by the lines of force that were passing through the particular point in space where the object was located. The more lines of force that touched an object, the greater the magnetic force it experienced.

CAREERS IN PHYSICS

Charged Up by Electromagnetism

Dr. Catherine Kallin

Superconductors are materials that, at extremely low temperatures (usually below –150˚C), conduct electricity with absolutely no resistance. Normal wires always have at least a little resistance, and some of the electricity they carry is lost and becomes thermal energy. Superconducting wires do not do this, no matter how long they are.

Superconductors also have many unusual magnetic properties. They can form perfect barriers to a magnetic field, and can "remember" a magnetic field even when the field is turned off. Many devices that now make use of magnetism — electric motors, power generators, audio devices, and computer memories — will become more powerful, more efficient, and much smaller with advances in superconductivity. In fact, superconductors are already being used in magnetic resonance imaging (MRI) and elsewhere.

To find improved superconductors, we need to understand better how superconductivity works. For example, scientists are continually finding new superconductors that work at warmer and more easily maintained temperatures. Dr. Catherine Kallin, a professor at McMaster University in Hamilton, Ontario, is working at the very frontier of superconductor research, making use of some of the most challenging and difficult theories of magnetism.

"My own research studies 'vortices' in superconductors — small whirlpools of circulating supercurrent, similar to water swirling down a drain or air in a tornado. When a superconductor is placed in a magnetic field, the magnetic field penetrates the superconductor in filaments that lie at the centre of each vortex," she explains.

Dr. Kallin decided on a career in theoretical physics because of her interest in mathematics and a desire to do research that she could talk about concretely: "This element of being able to explain my work to others was very important to me." Dr. Kallin's mathematical interests were encouraged by a Grade 10 math teacher. This teacher suggested that she form a study group with her friends who perhaps "did not share my interest in mathematics." The experience helped improve her friends' grades and kindled in her "a deep love of both discovering new math and teaching it to others."

Going Further

1. Many companies routinely use superconductivity in their products. Find out the names of some of these companies and contact them to discover how they use superconductivity. How many applications for this interesting phenomenon are already in place?

2. Form your own study group with some of your friends and investigate superconductivity. A good place to start is the Oak Ridge National Laboratory Internet site. Try explaining the effect to another student, a parent, a sibling, or your classmates.

Web Link

www.school.mcgrawhill.ca/resources/

Does Professor Kallin's work make you feel you might be interested in a career in physics? If so, go to the above web site to find out more about careers in physics.

INVESTIGATION 14-A

Patterns in Magnetism

TARGET SKILLS
- Identifying variables
- Conducting research
- Communicating results

The patterns created by sprinkling iron filings around magnets had been observed as far back as the middle of the thirteenth century. In this investigation, you are going to study these patterns from various frames of reference in order to gain a better understanding of the nature of magnetism and magnetic forces.

If you performed the "Try This" experiment on page 671, you know that magnets induce magnetism in materials such as iron. The iron filings that are sprinkled around a magnet are induced to become hundreds of tiny magnets. Because the inertia of the iron filings is very small, they are easily oriented by the magnetic forces exerted on them. In this way, they form patterns that indicate the direction of magnetic forces in the region around a magnet. Because the patterns formed by the iron filings were like the patterns in a field after it has been plowed, these patterns became known as magnetic fields.

Problem

The object of this investigation is to use iron filings to plot the magnetic field lines for bar magnets.

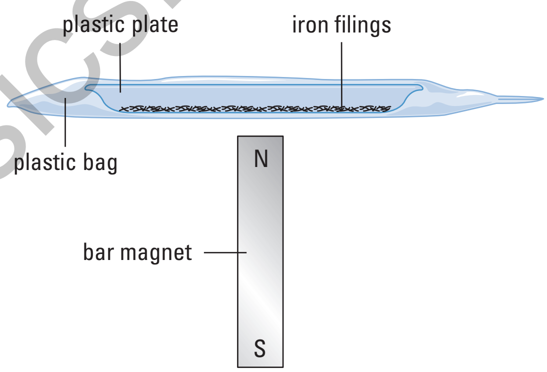
Equipment

- bar magnets (2)
- plastic or smooth paper plate (about 20 cm diameter)
- sealable plastic bag (such as a Ziploc bag)
- iron filings

Part 1: Using one bar magnet

Procedure

1. Place the plate and some filings in the plastic bag. In this way you will be able to re-use them several times without losing them.
2. Tip the bag and collect the filings on the plate. Gently shake the filings so that they are evenly distributed over the surface of the plate.
3. Stand the bar magnet on its end on the table with the N-pole at the top. Hold the plate over the magnet so that the magnet is perpendicular to the centre of plate. (Someone will need to hold the magnet so that it does not fall over.)
4. Gently tap the plate so that the filings align themselves with the magnetic field of the magnet (see below).



5. Draw an accurate sketch of the pattern formed by the filings. Try to include some sense of the third dimension in your sketches.
6. Move the plate away from the magnet and shake it so that the filings are spread uniformly over the plate again.
7. Reverse the polarity of the magnet on the table (turn the other end up) and repeat steps 3 through 5.

8. Move the plate away from the magnet and shake it again so that the filings are spread uniformly over the plate.
9. Place the magnet flat on the table. Place the plate on the magnet so that the magnet is roughly centred underneath.
10. Gently tap the plate so that the filings align themselves with the magnetic field.
11. Draw an accurate sketch of the pattern formed by the filings.
12. Repeat steps 8 to 11, placing the narrow side of the magnet in contact with the underside of the plate.

Part 2: Using two bar magnets

Procedure

1. Spread the iron filings uniformly over the surface of the plate.
2. Place two bar magnets about 3 cm apart, perpendicular to the bottom of the plate. Have the N-pole of one and the S-pole of the other pointing upward.
3. Gently tap the plate so the filings align themselves with the magnetic field of the magnets. Make an accurate sketch of the observed pattern.
4. Spread the iron filings uniformly over the surface of the plate.
5. Place the two bar magnets with their largest surfaces on the table so that the long axes are lined up. The N-pole of one magnet should be about two centimetres away from the S-pole of the other.
6. Place the plate on top of the magnets. Gently tap the plate so that the filings align themselves with the magnetic fields. Make a detailed sketch of the observed pattern.
7. Repeat steps 4 to 6 with the magnets turned so that their narrow edges are on the table.

Part 3: Two bar magnets, N-poles close

Procedure

1. Repeat Part 2 of the investigation, placing two N-poles (or two S-poles) near each other, rather than one N-pole and one S-pole.

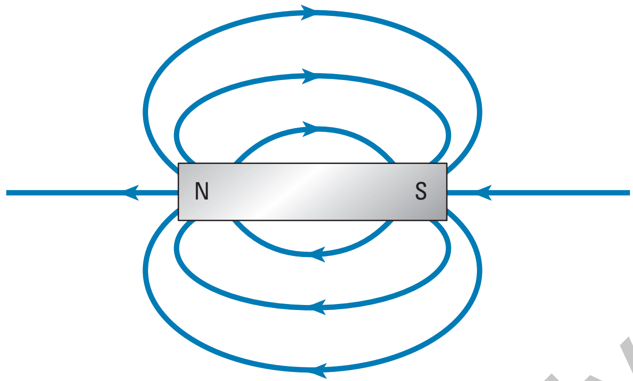
Analyze and Conclude

1. Use the following to analyze Part 1 results.
   (a) In the first two sketches, if you didn't know which pole was under the plate, would it be possible to tell from the sketches?
   (b) In the final two sketches, could you tell which pole of the magnet was at which end of the field by looking only at the pattern?
   (c) Examine the shapes of the magnetic fields in your sketches. Can you tell where the field is strongest (where the magnet would exert the largest force on an object)? This becomes a basic premise of Field theory.
   (d) You have seen the field pattern from three different angles. Using all of the information gathered in your sketches, extrapolate them into a three-dimensional picture of the field around the magnet.
2. Use the following to analyze Part 2 results.
   (a) Is there any way to determine which is the N-pole and which is the S-pole of the magnets just by looking at the pattern?
   (b) From your sketches of the three different views of the field pattern, make a three-dimensional drawing of the field.
3. Create a three-dimensional drawing of the field for Part 3, as you did for Part 2.

Apply and Extend

4. Look at your sketches from Parts 2 and 3 of this investigation. Is there anything about them that would imply that "like poles repel" and "unlike poles attract"? Explain.

Figure 14.9 From the two-dimensional drawings of iron filings around magnets, you can create idealized two-dimensional images of the magnetic field. Notice how the lines get farther apart where the field is weaker.



Lines of Force

You probably have noticed that as the distance from a magnet increases, the lines of force get farther apart. When an object is close to a magnet, the lines of force are more densely packed. The patterns of the lines of force in space are called **magnetic fields**. Thus, close to the magnet, many lines will act on the object causing it to experience a large magnetic force. When the object moves farther away from the magnet, the density of the lines of force is reduced, as is the magnetic force. In fact, the term **field density** is synonymous with **field strength**. When you draw magnetic fields, you must make sure that the spacing between the lines indicates the strength of the field.

Force is a vector quantity. Since the lines of force act to exert forces in particular directions, they must also be vectors. The magnetic fields from a magnet can exert forces in opposite directions, depending on the polarity of the affected object. Obviously, the field cannot point in two directions at once. To resolve this dilemma, the direction of the field lines of force has been arbitrarily assigned.

To scientists living in the Northern Hemisphere, the N-pole of the compass was a natural choice as the reference pole. By definition, the direction of a line of force is the same direction as the force that the field exerts on the N-pole of a magnet. Thus, the lines of force must point away from the N-pole of a magnet and toward the S-pole of a magnet. A magnetic S-pole, therefore, experiences a force in the opposite direction to the direction of the line of force. When a magnetic field is drawn, arrowheads must be included on the lines of force to indicate their direction and thus the direction of the magnetic field (see Figure 14.9 above). Figure 14.10 provides you with a three-dimensional view of the magnetic field.

ELECTRONIC LEARNING PARTNER

Further information about magnetic fields is available on your Electronic Learning Partner.

Figure 14.10 A suspension of iron filings in glycerine is used to demonstrate the third dimension of a magnetic field.

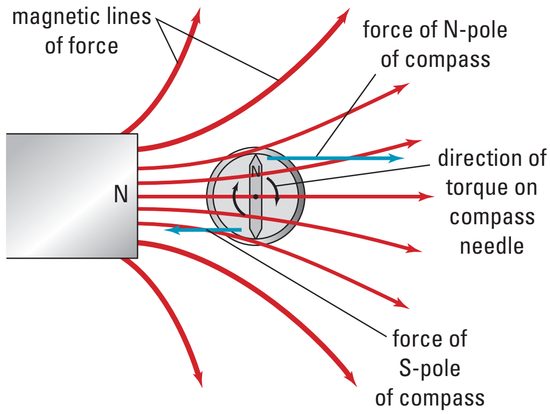


Figure 14.11 A magnetic dipole, such as a compass needle, experiences a torque (twisting force) that aligns it with the surrounding magnetic field.

When a magnetic dipole (all magnets are dipoles) is placed in a magnetic field, its N-pole experiences a force in the direction of the line of force, and its S-pole experiences a force in the direction exactly opposite to the direction of the line of force. As a result, the dipole experiences a force that causes it to become aligned with the line of force, with its N-pole indicating the direction of the line of force. This explains how magnetic compasses and dip needles work. It also explains why magnets do not always point directly at the nearest magnetic N- or S-pole (see Figure 14.11).

Earth's Magnetic Field

If you revisit Gilbert's model of Earth as a magnet, you can now imagine what the magnetic field must be like and why the magnetic compass and dip needle act as they do. The magnetic lines of force exit Earth's surface in the magnetic Southern Hemisphere and re-enter the surface in the magnetic Northern Hemisphere as shown in Figure 14.12.

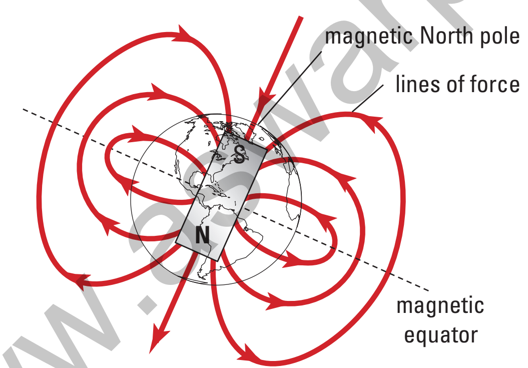


Figure 14.12 Earth is enveloped by a magnetic field called the magnetosphere that extends far into space.

The location where the magnetic lines of force are parallel to Earth's surface is known as the magnet equator. At that point, a dip needle is horizontal. As you move closer to either of Earth's magnetic poles, the lines of force slope more and more steeply to the surface. At the magnetic poles, the lines of force are perpendicular to Earth's surface.

PHYSICS FILE

Michael Faraday (1791–1867) was the son of a blacksmith who had been apprenticed to a bookbinder when he was about 13 years old. Faraday began to read the books that came into the shop for binding. He was especially fascinated by the books about science and began to attend lectures in science given at the Royal Institute in London. In 1812, Faraday applied for a position at the Institute and was given a job as a research assistant.

Faraday proved to be a brilliant experimenter. However, as he had little formal education, he was not very good at mathematics. Thus, when it came to the study of magnetism, Faraday found the conceptual approach of drawing fields to explain how magnets interacted more to his liking than the mathematical approach used in the action-at-a-distance theory.

The entirety of the magnetic field around Earth is called the magnetosphere. Figure 14.13 shows an artist's rendering of the magnetosphere. The highly charged solar winds from the sun tend to "blow" the magnetosphere so that it is flattened on the side nearest the sun and elongated on the side away from the sun. It is the magnetosphere that protects Earth from the harmful effects of the solar wind. Electric charges from the solar wind can become trapped in the magnetosphere. As they spiral down inside the magnetosphere, they interact with the atoms and molecules in the atmosphere to produce an eerie light known as the aurora.

PHYSICS IN THE NEWS

Solar Graffiti

The year 2000 marked a banner year in our understanding of solar phenomena and Earth's weather. Until then, adequate forecasting tools remained unavailable to researchers, leaving Earth a victim of solar flares (explosions on the Sun's surface), magnetic storms, and coronal mass ejections (CMEs). CMEs are explosions in the atmosphere surrounding the Sun. For example, on March 13, 1989, during a peak in sunspot activity there was a breakdown of the Quebec hydro-electric grid causing massive power disruptions for hours throughout the province. Today, however, scientists are armed with powerful new knowledge. CMEs, believed to be the most potent force in space weather, are usually preceded by a particular S-shaped formation on the surface of the Sun (see the "S" shape on the image of the Sun, in the figure).

Sunspots are intense concentrations of the Sun's magnetic field on its surface. Loops of magnetism can form between pairs of sunspots of opposite magnetic polarity, gaining potential energy like a rubber band being stretched to its limit; these are observed as an S-shaped formation on the surface. When the S is fully formed, these bands of energy "snap," releasing bursts of energy that result in CMEs. A "wind" of highly energized particles ensues, travelling at such speeds that it can reach Earth in a matter of days.

Fortunately, Earth's own magnetic field (the *magnetosphere*) can protect us most of the time. It absorbs or deflects much of the Sun's released energy, but under extreme conditions, the magnetosphere can become overloaded, resulting in a *geomagnetic storm*. Here, the overloaded magnetosphere offloads excess energy in the form of a shower of highly energetic particles directed at Earth's surface. When these hit the upper atmosphere, the effects can be seen in the form of the *aurora borealis*.

Sometimes even the atmosphere can't stop the rain of energy, and parts of Earth's surface are bathed in a powerful moving magnetic field. Power lines are especially susceptible; whenever any conductor moves through a magnetic field, it induces an electric current. When a geomagnetic storm washes over power lines, it likewise induces a current spike, in exactly the same way that power is produced in an electric generator. This is what happened in Quebec. A particularly powerful geomagnetic storm produced excess current in the power lines causing a power overload.

The need for good prediction tools is clear. From now on, special attention will be paid to the "writing" on the Sun!

Domains Revisited

A material is **ferromagnetic** if its atoms or molecules are magnets and they tend to group into domains. When a ferromagnetic material is placed in a magnetic field, the lines of the field find it easier to pass through the material than the space around the material. Ferromagnetic materials have a large magnetic permeability. When the magnetic lines of force pass through the material, they act on the domains within the material and cause them to become aligned. At this point, the ferromagnetic material is a magnet in its own right and has its own magnetic field that is aligned with and enhances the original magnetic field. Ferromagnetic materials are so permeable to magnetic lines of force that they are able to react well with even very weak external magnetic fields. Materials such as iron, nickel, cobalt and steel are ferromagnetic.

The atoms or molecules of **paramagnetic** materials are magnetic but the material is not very permeable to magnetic fields. Thus, if the external magnetic field is weak, the material shows very little or no magnetism. The magnetic effects become noticeable at room temperature, and only if the external field is very strong. With a weak field, the permeability is so small that it cannot overcome the thermal activity of the atoms in order to align the domains. As soon as the external field is gone, the small amount of magnetism that was induced in the material disappears. However, if the temperature is very low, the internal thermal activity of the material is reduced. Any external field can align with the domains more easily and the material exhibits magnetic behaviour similar to a ferromagnetic material. Aluminum is a paramagnetic material as are many gases. Will any magnetic properties be detected for aluminum?

A third type of reaction of a magnetic field is called **diamagnetism**. Diamagnetic materials are less permeable than air. They never show ferromagnetic properties but become very weakly magnetized in the *opposite* direction to the applied field. Like paramagnetic materials, they need very strong magnetic fields or very cold temperatures before they exhibit any of their characteristic behaviour. The atoms of diamagnetic materials are not magnetic and thus do not form domains. The diamagnetism results from the motion of the electrons within the atoms of the material. How this occurs will become clearer when you study Lenz's laws in the next chapter. Materials such as copper, rubber and glass are diamagnetic.

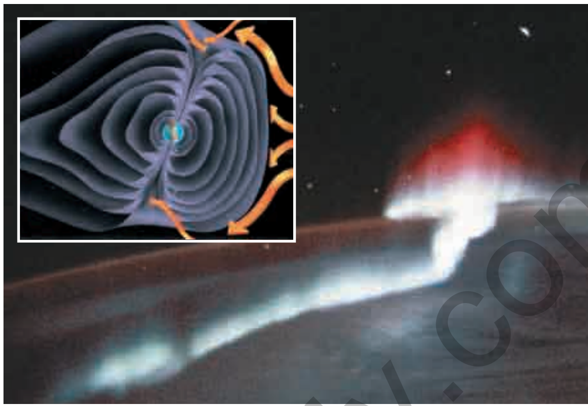


Figure 14.13 The magnetosphere envelops Earth, protecting it from the effects of the solar wind. As electric charges from the solar wind are captured by the magnetosphere, they spiral down into the atmosphere. When they reach the atmosphere, they cause the atmospheric gases to become ionized and emit light. Depending on the hemisphere in which it occurs, that light is called the aurora borealis or the aurora australis.

TRY THIS...

Build a chain of hanging paper clips by placing them end to end suspended from a bar magnet. Continue to add paper clips until the magnet will no longer support additional paper clips. Hold the top paper clip in the chain as still as possible, and carefully remove the magnet from above it. Have your partner record some observations. Now bring the other pole of the magnet near the top of the chain and observe. Predict what type of material must be contained within paper clips and provide justification for your predictions. Create a model to explain how a magnet might enable the paper clips to attract one another. When you removed the magnet, did all of the paper clips fall away? Does your model predict this behaviour? Finally, is your model able to explain the results observed when the opposite magnetic pole was brought near the paper clip chain?

INVESTIGATION 14-B

The Vector Nature of a Magnetic Field

TARGET SKILLS

- Performing and recording
- Analyzing and interpreting

Magnetic fields are vector quantities. Thus, if a compass is placed in a magnetic field, it aligns itself in the direction of the net magnetic field at that point in space. In this investigation, you will trace the direction of the magnetic field in the vicinity of a bar magnet, and the direction of the magnetic field at greater distances from the bar.

Problem

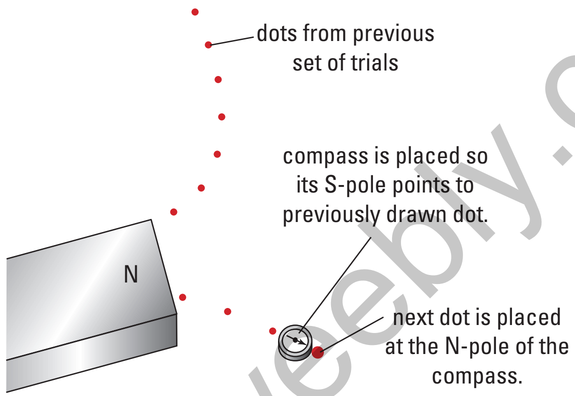
What do you observe when two or more magnets create fields in the same region of space?

Materials

- bar magnet
- compass (about 2 cm in diameter)
- large sheet of paper (approx. 60 cm × 60 cm)

Procedure

1. If a large sheet of blank newsprint is not available, tape together several sheets of paper to form a sheet about 60 cm × 60 cm. Place the paper on the floor or on a table. Use the compass to find the direction of Earth's magnetic field and draw an arrow on the paper representing that direction.
2. Place the bar magnet horizontally at the centre of the sheet. The direction of the long axis of the bar magnet is not important. Trace an outline of the bar magnet and indicate, within the outline, the location of the magnet's N-pole.
3. Place the compass so that it touches the bar magnet near its N-pole and draw a dot at the N-pole of the compass needle.
4. Move the compass so that the S-pole of its needle is at the dot you just drew on the paper and draw another dot at the N-pole of the compass needle. Use the diagram on the upper right as a guide.
5. Continue this process until the compass returns to the magnet or goes off the paper.



6. Trace a line through the series of dots you just drew on the paper. Make sure you include an arrowhead on your line to indicate the direction of the line of force.
7. Choose several more starting points at the ends of and along the sides of the bar magnet and repeat the previous steps.

Analyze and Conclude

1. Did the compass trace out a pattern similar to the one you observed when you sprinkled iron filings on the bar magnet?
2. Using your knowledge of vectors and fields, explain why the lines you traced followed the observed paths. If you imagine how the field from the bar magnet and Earth are interacting, it will help you understand the pattern traced by the compass.

Apply and Extend

3. If time permits, repeat the investigation using the bar magnet in a different orientation.
4. Try the investigation with two or three bar magnets placed on the sheet in various configurations.

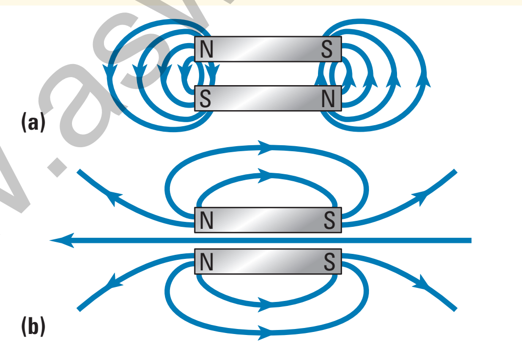
Field versus Action-at-a-distance

According to the Action-at-a-distance theory, Earth's Magnetic North pole was assumed to attract the N-pole of a compass. Now that Field theory has replaced the Action-at-a-distance theory, rather than being attracted by the Magnetic North pole, the magnetic field surrounding Earth causes the compass needle to become aligned with it. Earth's magnetic field, not the magnetic north-pole, acts on the compass needle. Why choose one theory over the other? Don't they both give the same result?

In science, theories come and go depending on their ability to *explain* and *predict*. As you proceed through the study of physics you will find many instances where the ability of the Field theory to explain and/or predict is far superior to the Action-at-a-distance theory. In fact, it would be very difficult to imagine modern physics without Field theory. In your Grade 12 physics course, you will explore in greater depth the concepts of Field theory as applied to gravity, electricity, and magnetism.

14.2 Section Review

1. I The figure below shows two arrangements of equal-strength bar magnets parallel to each other. Based on your results from Investigations 14-A and B, draw what you would expect to find if you plotted the magnetic field for this arrangement. Base your diagrams on your observations of the nature of the fields when like and unlike poles were placed near each other in Investigation 14-A. You may want to verify your answers using iron filings and bar magnets.



2. C Magnetic lines of force are known to be passing through a circular iron plate in a direction parallel to its axis. What does this tell you about the magnetic polarity of the plate? Draw a sketch to demonstrate your answer.
3. K/U Using Field theory, explain why placing a ferromagnetic material between a magnet and a magnetic compass causes the compass to experience a greater magnetic force?
4. K/U Using Field theory, explain why placing a paramagnetic or diamagnetic material between a bar magnet and a magnetic compass causes no noticeable reaction in the compass. Under what conditions would you expect paramagnetic or dia-magnetic materials to produce a reaction in the compass?

14.3 Electricity and Magnetism

SECTION EXPECTATIONS

- Describe the relationship between magnetic fields and electric current.
- Analyze and predict, by applying the right-hand rule, the direction of current produced a magnetic field.
- Interpret and illustrate, using experimental data, the magnetic field produced by a current flowing through a conductor.

KEY TERMS

- electromagnetism
- right-hand rules #1 and #2
- solenoid
- magnetic monopole

Figure 14.14 Superconductors allow physicists to generate extremely powerful magnetic fields.

In order to complete research into atomic structure, atoms are bombarded with particles which have extremely high energy. To focus and direct particles with such great energies requires very powerful superconducting electromagnets. Superconducting electromagnets, like the one in the photograph, can produce magnetic fields more than 150 000 times stronger than Earth's magnetic field.

Electric Charges and Magnetic Poles

In spite of the similarities between electricity and magnetism, early experimenters considered them to be two entirely separate phenomena. It is true that both electrostatic and magnetic forces of attraction and repulsion become weaker with separation. However, they display many fundamental differences. Electric charge, the source of the electric force, moves easily through conductors, while magnetic poles, the source of the magnetic force, cannot be conducted. Almost anything can be given an electric charge. However, magnetic poles are normally found in only ferromagnetic materials. Like magnetic poles, there are two kinds of electric charges. Objects displaying electric charge usually have only one type of charge on them, positive or negative. Magnetic poles seem always to come in pairs, hence the magnetic dipole. Overall, it seemed that the differences were far more significant than the similarities.

PHYSICS FILE

Magnetic Monopoles

Whether or not a magnetic monopole can exist is an interesting point. As you will see later in this chapter, Field theory seems to predict that a magnetic monopole is not possible. Still, it is an attractive idea and scientists are still trying to decide whether or not they are possible. In the meantime, nobody has ever seen or been able to create a magnetic monopole in a laboratory.

Oersted's Discovery

In 1819, a Danish physicist, Hans Christian Oersted (1777–1851), was demonstrating the heating effects of an electric current in a wire to some friends and students. On his table he had some compasses ready for a demonstration he was doing later that day in magnetism. He noticed that when he closed the circuit, the needles of the compasses were deflected at right angles to the conductor. He kept this to himself until he had a chance to explore it further. It did not seem to make sense that the compass needle was neither attracted nor repelled by the current but deflected at right angles to it. Oersted had discovered that a current-carrying conductor caused the needle of a magnetic compass to deflect at right angles to the conductor. When he published his findings, it set off a flurry of research into the newly discovered phenomenon called **electromagnetism**. That is, moving electrons produce a magnetic field and a changing magnetic field will cause electrons to move.

Right-hand Rule #1

Oersted's experiments convinced him that each point of a current-carrying conductor created a magnetic field around itself. The lines of force for that field were a set of concentric closed circles on planes perpendicular to the direction of the current. The direction of the lines of force and thus the direction of the field could be determined using a "right-hand rule" (see Figure 14.15).

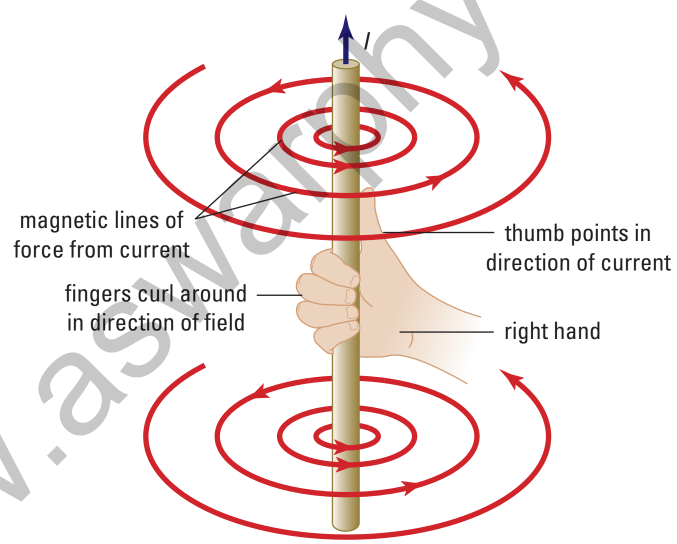


Figure 14.15 **Right-hand rule #1** If you grasp a current-carrying conductor with your right hand so that the thumb lies along the conductor in the direction of the current, then the fingers of your hand will be encircling the conductor in the direction of the magnetic lines of force caused by the current.

INVESTIGATION 14-C

Magnetic Field around a Straight Conductor

TARGET SKILLS
- Performing and recording
- Modelling concepts
- Communicating results

CAUTION In this experiment, you will be using circuits without a resistance to protect the power supply. They are *short circuits*. To protect the power supply from damage, you should only connect them for very short periods of time.

Problem

Develop an understanding of the relationship between a current and its magnetic field.

Prediction

In the text it is noted that Oersted observed that the needle of the compass was deflected at right angles to the current. From this information, what can you predict about the shape of the field near the conductor?

Equipment

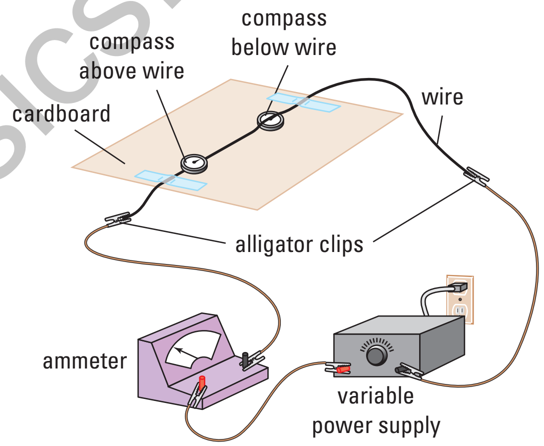
- ammeter (0–10 A)
- variable power supply (or fixed power supply with an external variable resistor)
- magnetic compass (2)
- wire (approximately 1 m)
- connecting leads
- cardboard square (approximately 20 cm × 20 cm)
- iron filings
- metre stick
- 1 kg mass (2)
- masking tape
- retort stand (2)
- ring clamp

Part 1: Horizontal Conductor

Procedure

1. Place the wire across the middle of the cardboard square and hold it in place at the edges of the cardboard with masking tape.
2. Connect the power supply and the ammeter, in series, with the wire.
3. Turn on the power supply very slightly to check that the ammeter is connected properly.
4. Once you have confirmed that the circuit is properly connected, place one compass under the wire and one compass above the wire. Rotate the cardboard until the wire lies along the direction of magnetic north and the compass needles are parallel to the conductor (see the figure below).

   (**Note:** Place the compasses far enough apart so that they do not strongly interact with each other. Tap them gently to make sure that their needles are able to move freely.)



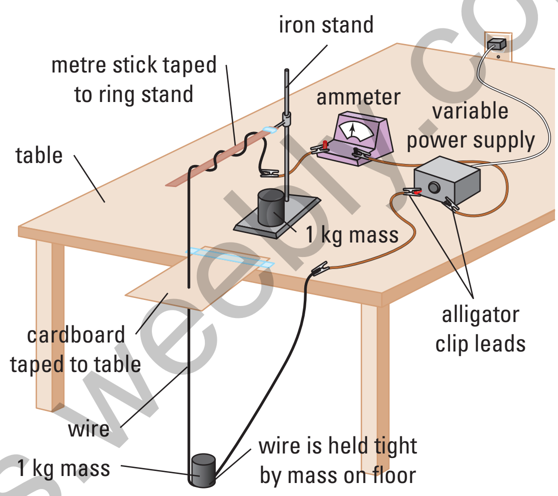
5. Turn the power on and increase the current (to about 5 A) until the needle of the compass shows a strong reaction to the current. Quickly disconnect the lead at the *anode* of the power supply. (In this way, you will not have to reset the power level each time you want to start and stop the current.) Next, momentarily touch, but do not attach, the lead to the anode of the power supply and note the reaction of the compass needles.

6. Draw a sketch of the orientation of the apparatus, including the direction of the current and the direction of the N-pole of the compasses before and after the current was turned on. (Remember that a magnetic dipole aligns itself with the net magnetic field. Also, the N-pole of a magnet is used as a reference to determine the direction of the magnetic field.) As a reference, include an arrow in your sketch to show the direction of Earth's magnetic field.
7. Draw a sketch of your observation of the reaction of the compass needles to the current.
8. Turn the cardboard 45° clockwise and repeat steps 5 through 7.
9. Turn the cardboard another 45° clockwise and repeat steps 5 through 7.
10. Turn the cardboard another 45° clockwise and repeat steps 5 through 7.
11. Without changing the power setting on the supply, reverse the connection of the leads connected to the wire on the cardboard so that the current in the wire is reversed. Reorient the cardboard to its original position. Momentarily turn on the current and note the reaction of the compass needles to the current. Draw a sketch of your observations.

Part 2: Vertical Conductor

Procedure

1. Assemble the apparatus as shown below.
2. Connect the power supply and ammeter to the wire and turn the current on very slightly to check that the ammeter is connected correctly.



3. Place a compass on the cardboard platform to the north of the conductor so that it is very close to, but not touching, the wire.
4. As in Part 1, momentarily turn on the current and increase it until the compass reacts to the current. Once again, a current of about 5 A should be adequate. (If you want to increase the current beyond that level, consult with your teacher.) Observe and note the reaction of the compass to the current.
5. Draw a sketch of the result, showing the position of the compass needle before and after the current was turned on. As a reference, include an arrow to show the direction of Earth's magnetic field.
6. Move the magnet 45° clockwise and repeat steps 4 and 5. Record your result on the sketch you drew for the first trial.

continued ▶

continued from previous page

7. Continue to move the compass around the conductor in 45° angles until it has returned to its original position, repeating steps 4 and 5 after each move.
8. Cut a slit in a piece of paper from its edge to its centre and use it to cover the cardboard square. Sprinkle iron filings on the paper around the conductor.
9. Connect the circuit and gently tap the cardboard. Observe the effect of the current on the position of the filings. Draw a sketch of the result.

Analyze and Conclude

1. For all trials in Part 1, determine the greatest angle that the current caused the compass needle to deflect? What is the significance of this? Remember that the compass needle points in the direction of the sum of the magnetic fields from the Earth and from the current.
2. In Part 1, what is the significance of the fact that the compass needles above and below the current deflected in opposite directions?
3. In Part 1, when you reversed the current without changing the orientation of the wire, what happened? Why is that significant?
4. In Part 1, based on the information that you have gathered, what is your prediction for the shape of the magnetic field near a current? Explain.
5. Do the results from Part 2 of the investigation confirm the hypothesis you made about the shape of the field in Part 1?
6. In the previous sections of this chapter, you saw magnetic fields pointing from the N-pole of a magnet to the S-pole. Where are the poles for this magnetic field? Where do the magnetic lines of force begin and end?
7. Does the magnetic field from the current maintain its strength as you move away from the current? What evidence is there to support your answer?
8. What is your conclusion about the shape of the magnetic field that results from a current?

Apply and Extend

9. What would be the effect if a second wire was positioned alongside the wire in your apparatus and was carrying a current in (a) the same direction or (b) the opposite direction as the wire in your apparatus? Form a partnership with another lab group, and combine your apparatuses to run two wires side by side. Using two power supplies to produce equal currents in the wires, repeat steps 4 and 5 of the previous procedure. Does this arrangement have an effect on the strength of the field around the wires? Try it with currents running in the same and in the opposite directions.
10. What do the results tell you about the nature of magnetic fields around conductors?

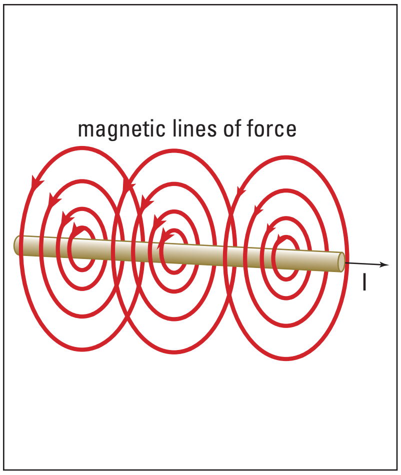


Figure 14.16 When the current is upward, right-hand rule #1 shows the field lines as indicated.

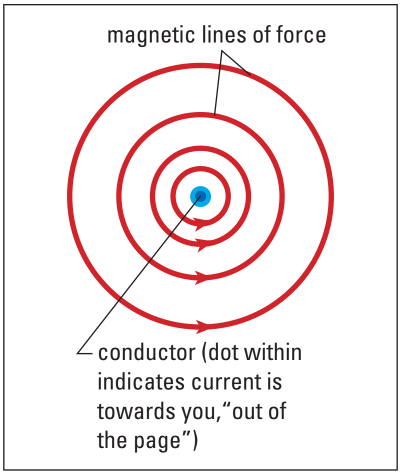


Figure 14.17 The system in Figure 14.29 viewed directly from above, without the benefit of perspective. The dot in the cross-section of the conductor indicates that the current is flowing through the conductor directly toward you (out from the page).

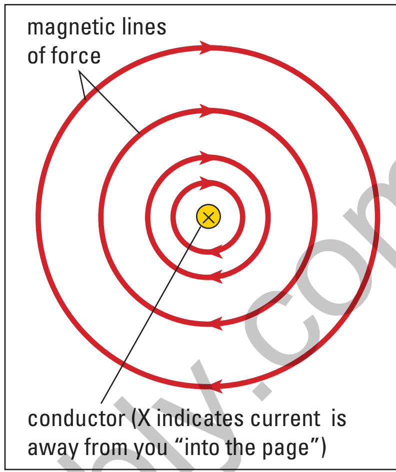


Figure 14.18 The diagram in Figure 14.29 viewed directly from below, without the benefit of perspective. The cross in the cross section of the conductor indicates that the current is flowing through the conductor directly away from you (into the page).

Drawing Field Diagrams

Using right-hand rule #1, diagrams of the magnetic fields around currents are easy to draw, but they do require drawing in 3-dimensions. Drawing in perspective is time consuming and often messy, so the ability to show the third dimension in a two-dimensional diagram offers the best solution.

A simple convention has been created to show a vector that is pointing directly at or directly away from you. If the arrow is pointing at you, a dot is used to represent the tip of the arrow. If the arrow is pointing directly away from you, a cross is used to represent the tail-feathers of the arrow as shown in Figure 14.16. Apply right-hand rule #1 to make sure you agree with the orientation of the current and the magnetic field in Figures 14.17 and 14.18.

Field Theory Wins

In the previous section of this chapter, there seemed to be no compelling reason to abandon the Action-at-a-distance theory in favour of the Field theory. Now the real advantage of Field theory over the Action-at-a-distance theory becomes clear. According to the Action-at-a-distance theory, one magnet acts directly on another magnet. That works well when there are two magnets, but how can you use the Action-at-a-distance theory to explain the magnetic force on the compass needle near the current-carrying conductor when there is no magnet to exert the force on the compass?

In Field theory, a field, rather than a magnet, is the source of magnetic forces. Oersted's discovery, which preceded Field theory by a few years, clearly proved that you do not need a magnet as the source of a magnetic force. When Faraday created Field theory, it provided a framework to discuss magnetic forces on the magnets near a current-carrying conductor. According to Field theory, the current created the magnetic field around itself and the field exerted the force on the compasses. As you discovered in your investigation, Oersted proved that the direction and strength of the magnetic force on the compasses depends on the direction and strength of the current. Field theory argues that the direction and strength of the current affects the direction and strength of the magnetic field around the magnet and that, in turn, affects the direction and strength of the magnetic force.

Magnetic Field of a Current-carrying Coil

Consider a coil of wire carrying a current as shown in Figure 14.19. What type of magnetic field should there be around the wire? Oersted's discovery predicts that there are circular magnetic lines of force perpendicular to the coil at each point on the coil. Inside the coil, all the magnetic lines of force pass through the plane of the coil in the same direction as determined using right-hand rule #1. Outside the coil, all lines of force pass through the plane of the coil in the opposite direction that they passed through inside the coil.

Examine the situation outside the coil. The lines of force from one edge of the coil point in the opposite direction to the lines of force from the edge diametrically opposite. Since they point in opposite directions, the two magnetic fields combine together destructively, making the field even weaker than it would be from a single edge.

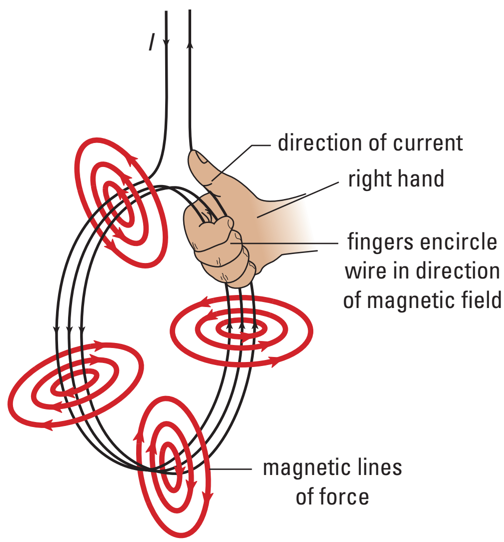


Figure 14.19 Using right-hand rule #1, we can show that, inside the coil, all the lines of force point in the same direction. The total strength of the magnetic field inside the coil is the vector sum of all the individual fields. Since all lines of force point in the same direction, the net magnetic field inside the coil is quite strong.

Next examine the situation inside the coil. A remarkable thing happens. The lines of force from all points on the coil pass through the plane of the coil in the same direction. Thus, the magnetic fields inside the coil combine together constructively. As you move away from one edge of the coil, along any diameter, the field strength from that edge weakens. However, as you move away from one edge, you move closer to the opposite edge, and the field from the opposite edge gets stronger at just the right rate to exactly compensate for the loss in strength from the other edge. The net effect is that the field is exactly uniform in strength.

When you draw the magnetic field for a coil, the lines of force should still be closed loops. Inside the coil, they should be uniformly spaced to represent the uniform nature of the field. Outside the coil, the magnetic lines of force should spread out to indicate the weakened field in that region. Figure 14.20 demonstrates this property if the coil was viewed in cross section. Figure 14.21 illustrates the same property of the coil when viewed in the plane of the coil from either face.

For the two current-carrying coils, dots and crosses represent the directions of the magnetic fields in the plane of the page. In the coil at right (b), the current is counter-clockwise, thus the magnetic field lines point out of the page inside the coil and into the page outside the coil. In the coil at left (a), the reverse is true. Inside the coils, the spacing of the magnetic lines of force is uniform to indicate the uniform nature of the field. Outside the coils, the spacing of the lines increases as the distance from the coil increases to indicate that the magnetic field strength is decreasing as you move away from the coil.

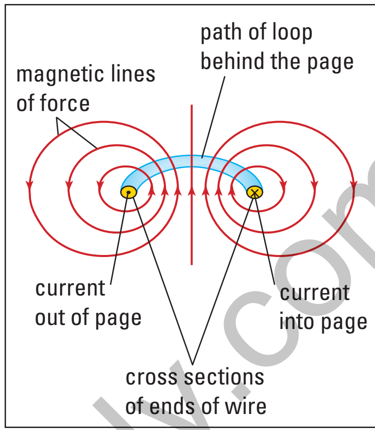


Figure 14.20 The lines of force around the edges of a coil are closed loops. Inside the coil, the line spacing indicates that the field is uniform. Outside the coil, the line spacing indicates that the field is getting weaker as the distance from the coil increases.

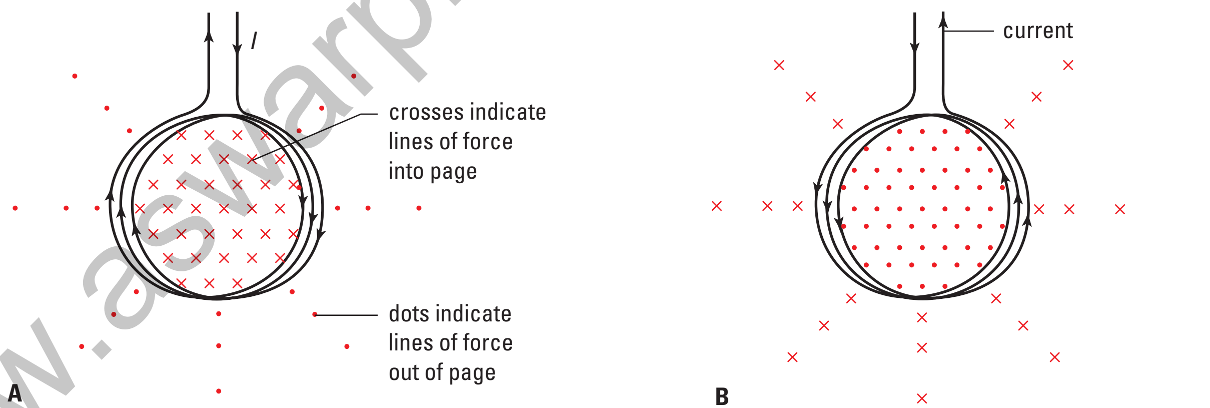


Figure 14.21 **(A)** Magnetic fields with a clockwise current

(B) Magnetic fields with a counter-clockwise current

INVESTIGATION 14-D

Magnetic Field around a Helix

TARGET SKILLS

- Hypothesizing
- Conducting research
- Performing and recording

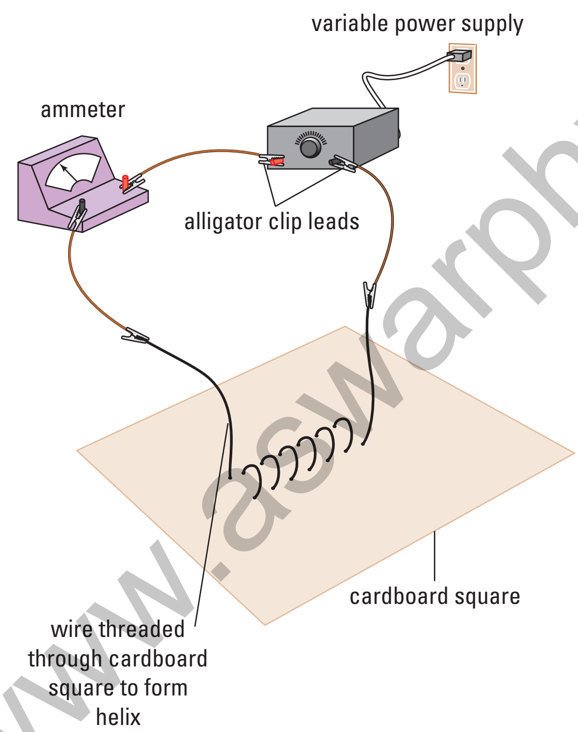
A helix is formed when a coil of wire is stretched so that there is space between the adjacent loops of wire. When a wire is formed into a helix and current flows through it, the magnetic field is similar to that of a coil, except that it is longer.

Purpose

The purpose of this investigation is to plot the shape of the magnetic field around a helix.

Hypothesis

Based on the information that you have about the magnetic field around a single coil of wire, draw a sketch to predict the shape of the magnetic field around the helix.



Equipment and Materials

- wire for helix (approx. 1 m)
- cardboard square (approx. 20 cm × 20 cm)
- power supply
- ammeter (0–10 A)
- compass
- iron filings

Procedure

1. Thread the wire through the cardboard square as shown in Figure 14.35. A helix of about 10 turns, with loops that are two centimetres in diameter spaced about one centimetre apart, works reasonably well. Connect the power supply and the ammeter in series with the helix.

CAUTION Since the circuit has no resistance other than that of the coil, it is a short circuit. To protect the power supply from damage, the coil should only be connected to the circuit for very short periods of time.

2. Increase the power output of the supply very slightly to check that the ammeter has been connected correctly.
3. When the connections are correct, increase the output of the power supply until the current is about 5 A, and then disconnect the lead from the anode of the power supply.
4. Place a compass near the end of the helix and briefly connect the circuit. Notice the orientation of the compass needle.

5. Draw a sketch to record your observations. Include the coils, the direction of the current in the coils, and the orientation of the compass needle before and after the current was on. This will be used later in your analysis.
6. Repeat steps 4 and 5, placing the compass at various locations around the helix. Include all the results on the sketch made in step 5.
7. Sprinkle iron filings on the cardboard. Make sure there are filings inside the helix as well as outside it.
8. Briefly connect the circuit. Tap the cardboard to assist the filings to become aligned with the magnetic field of the helix. After a few seconds, disconnect the lead from the anode. **Do not disturb the filings on the cardboard.**
9. Give the power supply a period of time to cool down and repeat step 8 to enhance the result of the trial. (This step may be repeated again if necessary.)
10. Draw an accurate sketch of the pattern of the iron filings observed in step 9.
11. From your sketch of the pattern of iron filings, and the directions of the compasses, make a "lines of force" drawing of the magnetic field for the helix as seen in the pattern of the iron filings. Include the pattern of the lines inside the helix. Using the information from the compass sketch in step 5, place arrows on the lines of force to indicate the direction of the field.

Analyze and Conclude

1. Does the magnetic field pattern resemble the one in your hypothesis? If not, try to explain why the actual field differs from your hypothetical field.
2. Is the magnetic field around a helix similar to any magnetic field observed previously? If yes, describe the similarities and the differences between this field and the previously observed field.

Apply and Extend

3. What would be the effect on the magnetic field around the helix if the number of loops was increased without the helix getting longer? This would, in effect, make the turns tighter together.

Magnetic Field around a Solenoid

A **solenoid** is a closely wound helix. The main difference between the field from a solenoid and the field from a helix is that the field from a solenoid is more uniform. Also, because there are so many coils of wire, it is much stronger for any given current. Outside the solenoid, the magnetic field closely resembles that of a bar magnet. Inside a solenoid, all the magnetic lines of force form closed loops. The lines of force leave one end of the solenoid, circle around and enter the other end of the solenoid, and then pass through the solenoid to their starting point.

With a bar magnet, Field theory predicts that the lines of force entering one end of a magnet are the same ones that exit the other end. Compare the magnetic field around the solenoid as shown in Figure 14.22 with that of the bar magnet as shown in Figure 14.9 on page 680. Compare the picture of the pattern of iron filings for a bar magnet (Figure 14.8) with the one you drew for the helix in Investigation 14-D.

If the N-pole of a compass or bar magnet were placed near the end of the solenoid at which the lines of force exit, it would experience a force pushing it away from that end, just as if that end were an N-pole of a solid. Similarly, the S-pole of a bar magnet placed near the end of the solenoid, at which the lines of force exit, would be pulled toward the solenoid. In other words, the solenoid acts just like a hollow bar magnet. The similarity between a solenoid and a bar magnet is just one of many clues that the lines of force in all magnets are closed loops that pass through the magnet.

If magnetic lines of force are always closed loops, it explains why magnets are always dipoles. As we have seen, the end of the magnet where the lines of force exit is the N-pole, and where they re-enter the magnet is the S-pole. To have a magnetic monopole, let's say an N-monopole, the magnetic lines of force would have to

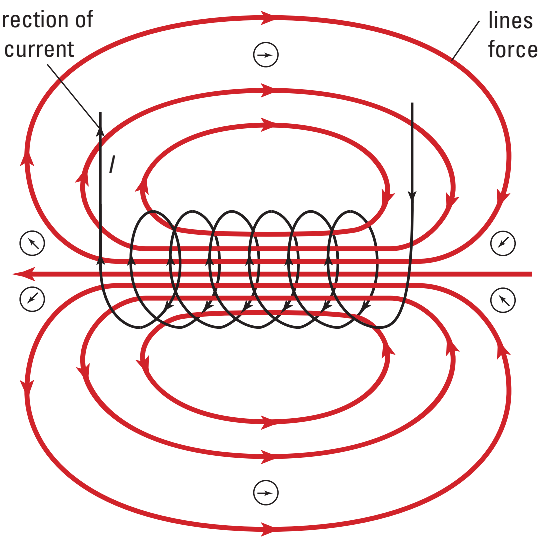


Figure 14.22 The pattern of the magnetic lines of force around a solenoid is very similar to the pattern of lines of force around a bar magnet.

exit the material but never re-enter it. If, as Field theory suggests, lines of force are closed loops, they must come back and enter the material at some point. That point is the S-pole of the material. When you break a magnet into pieces, you just shorten the path of the loops for each piece. They still are loops and each piece is still a magnetic dipole.

Right-hand Rule #2

How does the magnetic polarity of a coil or solenoid relate to the direction of the current in the coils? To find the N-pole of a coil of wire as shown in Figure 14.23, you can use right-hand rule #1. When you find the face of the coil where the lines of force exit, you have found the N-pole of the coil. Grasp the coil at some point with your right hand so that your thumb lies along the coil in the direction of the current, and your fingers encircle the wire in the direction of the magnetic lines of force. The face of the coil where your fingers exit is the N-pole of the coil.

To make this process simpler, a second right-hand rule was invented. It is actually just a variation of right-hand rule #1. **Right-hand rule #2**: Place the fingers of your right hand along the wire of the coil so that your fingers point in the direction of the current in the coil. When you extend your thumb at right angles to the plane of the coil, it will indicate the direction of the lines of force as they pass through the coil, and thus indicate the face of the coil that acts as the N-pole of the coil (Figure 14.24). The same rule will obviously apply to a solenoid or any other system where the current is moving in a circle.

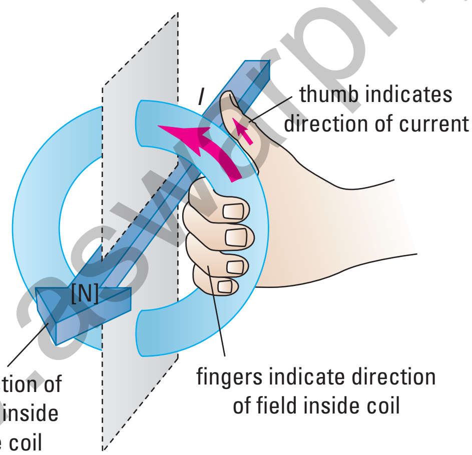


Figure 14.23 Right-hand rule #1 can be used to identify the direction of the lines of force through the coil and thus the locations of the N-pole and the S-pole of the coil.

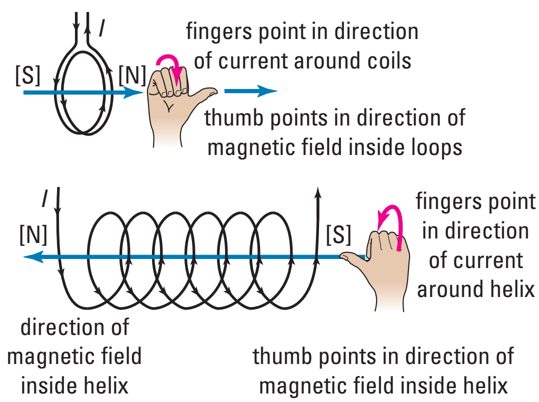


Figure 14.24 When the fingers of the right hand lie along a coil in the direction of the current in the coil, the thumb points in the direction of the magnetic lines of force inside the coil. The face of the coil where the magnetic lines of force exit acts like the N-pole of a magnet.

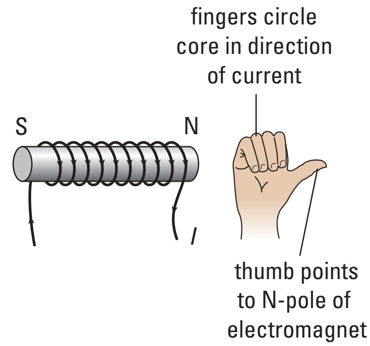


Figure 14.25 Right-hand rule #2 is used to locate the N-pole of an electromagnet.

Electromagnets

If a core of ferromagnetic material, such as iron, is placed inside a solenoid, the magnetic field strength inside the solenoid is greatly increased. Because of the permeability of the iron, the lines of force within the solenoid crowd into the iron core. This has two effects. First, the crowding concentrates the lines of force from the solenoid; the closer together the lines of force, the stronger the field. Second, the lines of force from the solenoid induce the domains of the iron core to align so that ferromagnetic material becomes a magnet whose field supplements the field of the solenoid.

The N-pole and S-pole of the electromagnet are located using right-hand rule #2. Grasp the electromagnet so that the fingers of your right hand encircle the magnet in the direction of the current around the core, and with your thumb parallel to the axis of the magnet. Your thumb points to the N-pole of the magnet (see Figure 14.25).

PHYSICS FILE

Magnetic recording equipment and the material on which it records is very sensitive to magnetism. Computer disks, audio tapes and VCR tapes all store data in the form of magnetic fields. The unwanted presence of a magnetic field near any of these media could easily erase all the stored data. For this reason, electronic engineers must design methods to protect the recording medium from the effects of the magnetic fields generated by the motors which run the systems.

Electromagnet Design

It is possible to make very strong electromagnets. Three factors affect the strength of an electromagnet: the size of the current, the number of turns, and the permeability of the core. For a core of a given material, it would seem that you just put more and more turns of wire around the core and increase the current. Unfortunately, it's not quite so simple.

Think back to your studies of electricity in the previous chapter. As the number of turns of wire around the core of a magnet increases, the resistance of the coil also increases ($R \propto l$). For a fixed potential difference, doubling the number of coils of wire around the core of an electromagnet doubles the resistance of the coils and halves the current through the coils. The result is no increase in the strength of the magnet. One solution is to use heavier wire. If the size of the magnet was not a factor, that solution might have merit. If size is a factor, then using heavier wire means that you cannot put as many turns around the magnet. Moreover, heavier wire would increase the mass of the coil and the cost of making it.

Another solution might be to increase the potential difference of the power supply to increase the current. This results in an increase in the power and thus the cost to operate the magnet. The increase in current to the coils of the electromagnet also means an increase in the amount of electrical energy that is converted to heat by the coils. Considering the importance of electromagnets to today's technology, finding the most efficient design for electromagnets is a formidable challenge.

If very strong magnetic fields are required, the magnets have to be super-cooled to the point where the coils become superconductors. At that point the coils lose their resistance and very large currents can flow through them. Many technical applications, such as high speed MAGLEV trains, magnetic resonance imaging (MRI) machines and particle accelerators, require the use of superconducting magnets.

The Source of Earth's Magnetic Field

Not long after the discovery of electromagnetism, scientists began to wonder if a current circulating around a solenoid created a magnetic field similar to a bar magnet, perhaps Earth's rotation had something to do with its magnetic field. In 1878, H. A. Rowland, an American physicist, showed that any group of charges moving in a circle would create a magnetic field. When he placed an electrostatic charge on a rubber disk and spun it on its axis, it produced a magnetic field similar to that of a solenoid. Today, most scientific theories of Earth's magnetism include the concept of the motion of charges deep in Earth's core.

PHYSICS FILE

There is evidence to show that Earth's magnetic field undergoes periodic reversals. It is not known whether the reversals occur gradually or rapidly. When lava containing ferromagnetic material cools below its Curie point, the domains within the rock tend to line up with Earth's magnetic field. In 1906, a French physicist, Bernard Brunhes, found some ancient lava rocks that were polarized opposite to Earth's magnetic field. He suggested that when these rocks solidified, Earth's magnetic field must have been reversed. Studies of lava around the world indicate that the last reversal occurred about 780 000 years ago, even though the time lapse between reversals seems to be about 200 000 years.

14.3 Section Review

1. **C** In each case, assume that the magnitudes of the currents in the conductors are the same. Indicate the relative field strengths on the diagrams by the spacing of the lines of force.
   - **(a)** Draw a conductor in cross-section as seen end on. Indicate a current flowing directly towards you (out of the page). Draw the lines of force for the magnetic field resulting from the current in the conductor.
   - **(b)** Draw a similar diagram to that in part (a), but showing a set of two conductors right next to each other. Indicate that the current in each conductor flows towards the viewer. Draw the lines of force diagram for the magnetic field that results from the current in the conductors.
   - **(c)** Draw a set of two conductors, as in part (b). Indicate that the current flows toward the viewer in one conductor and away from the viewer in the other conductor. Draw the lines of force diagram for the magnetic field that results from the currents in the conductors.
2. **K/U** When electromagnets are constructed, what types of materials should be used in the core to make the strongest magnet? Explain why it is an advantage to use one of these materials for the core of the electromagnet rather than just having an air-core solenoid as the magnet.
3. **MC** A conductor is aligned with Earth's magnetic lines of force. Thus, the compass set above the conductor points in a line parallel to the conductor. A DC power supply is connected to form a closed circuit with the conductor. Explain how this set-up could be used to identify the anode and the cathode for the power supply.

14.4 Magnets and Motors

SECTION EXPECTATIONS

- State the motor effect.
- Investigate and communicate factors that affect the force on a current carrying conductor.
- Test a device that operates using the principles of electromagnetism.

KEY TERMS

- right-hand rule #3
- motor effect
- rotor
- armature
- commutator
- split ring commutator
- torque

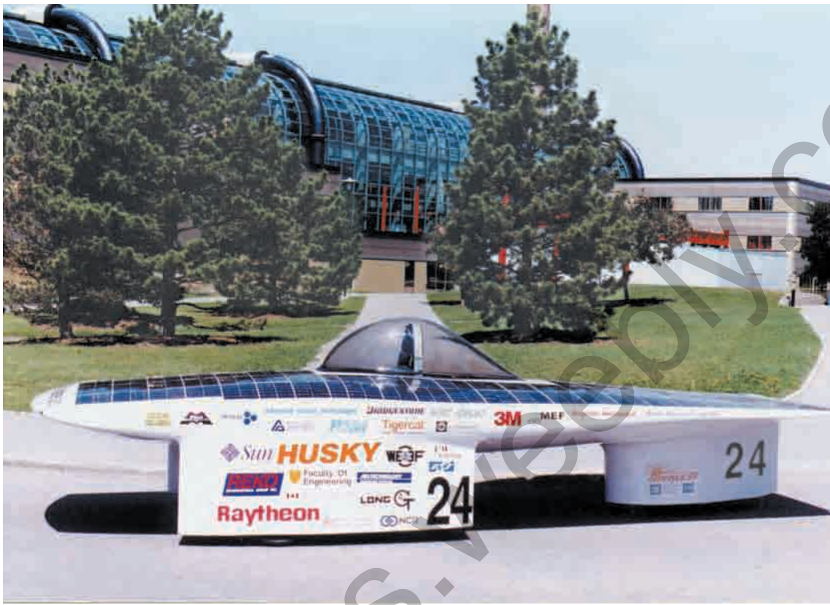


Figure 14.26 Designed to compete, the University of Waterloo's Midnight Sun solar-powered car attends races around the world.

University of Waterloo students are not alone in their effort to further solar-powered vehicle design. Undergraduate students at Queen's University set off in their solar-powered car on July 1, 2000 from Halifax and travelled 6500 km to Vancouver in less than a month. At the time this book was published, this event still held the world record for distance by a solar-powered vehicle. The electric motor was specially designed in a pancake shape to fit inside the low profile of the vehicle. Hybrid cars that use a combination of electric motors and gasoline engines are already gaining popularity.

The study of electric fields and electromagnetism in the previous section of this chapter is just the tip of the electromagnetic iceberg. Converting electrical energy to thermal energy is an easy task; you simply pass the current through a resistance and the resistance heats up. It was Oersted's discovery of electromagnetism that led to the invention of the electric motor. Currently, over half of the electricity generated in North America is used to run electric motors. It's fortunate that today's electric motors are so efficient; they typically operate at efficiencies greater than 80% in transforming electric energy into rotational motion of the motor, compared with a gasoline engine which operates at less than 30% efficiency.

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources*** and follow the **Physics 11** links for several laboratory activities on electric motor efficiency.

Electric Currents in Magnetic Fields

The first current meters, now called tangent galvanometers, consisted of a coil of wire with a compass needle at the centre. When the current flowed through the coil, the needle deflected to the east or west depending on the size and direction of the current. Because the tangent galvanometer had to be very carefully oriented, it was not particularly easy or practical to use (see Figure 14.27).

According to Newton's third law of motion, for every action there is an equal and opposite reaction. If the current in a conductor caused a magnetic field that exerted a force on a magnet, then the magnet must interact with the magnetic field from the current to exert a force on the conductor. In a tangent galvanometer, if the coil is exerting a force on the magnet at its centre to make it turn clockwise, then the magnet must be exerting a force on the coil trying to make it turn counter-clockwise.

The simplest form of the interaction of a magnet on a current-carrying conductor can be observed when a segment of wire carries a current linearly through a magnetic field. In Figure 14.28, a conductor carries a current upward past the N-pole of a bar magnet. First, let's approach this from the point of view of the conductor.

Using right-hand rule #1, as shown, the current creates a magnetic field consisting of circular lines of force around the conductor. The magnetic field of the conductor exerts a magnetic force on the N-pole of the magnet that acts in a direction tangent to the direction of the lines of force where they contact the magnet. (It is important to note that magnets do not react to their own magnetic fields.) Because of the magnetic field of the conductor, the N-pole of the bar magnet experiences a force directly into the page. If the N-pole of the magnet, in Figure 14.28, is free to move, it will move away from the observer into the page.

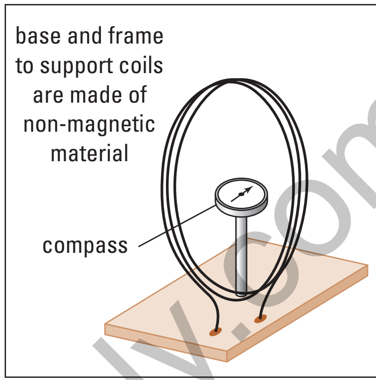


Figure 14.27 The coils of the tangent galvanometer are set so that the plane of the coils is parallel to the direction of the compass needle. When a current is passed through the coils, the compass needle deflects to the left or the right from that plane. The tangent of the angle of deflection is proportional to the size of the current.

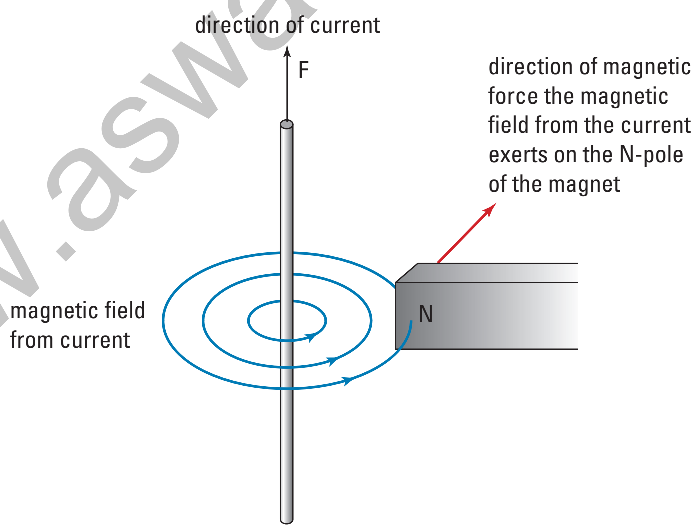


Figure 14.28 At the position of the N-pole of the bar magnet, the lines of force from the current's magnetic field point directly into the page; therefore, the N-pole of the magnet experiences a force directly into the page.

From the perspective of the magnet, it sees the conductor carrying a current through its magnetic field (Figure 14.42). Since the magnetic field from the conductor exerts a force on the magnet, Newton's third law says that the magnet exerts an equal, but oppositely directed, force on the conductor. Right-hand rule #3, describes the direction of the force exerted on the conductor from the magnet's perspective.

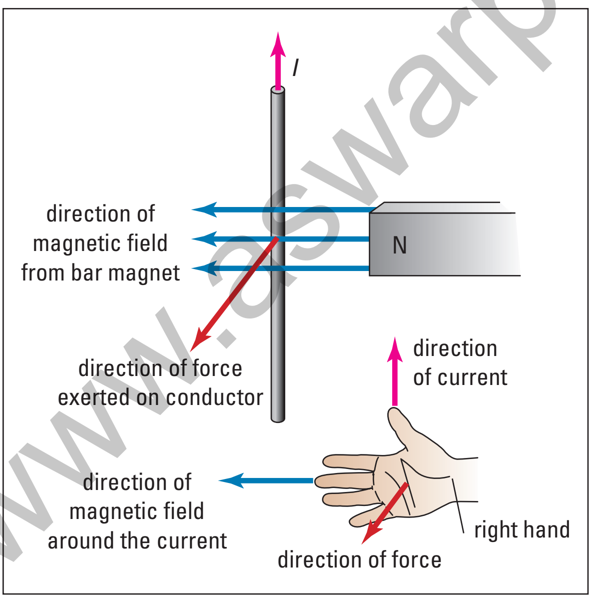
Right-hand Rule #3

Extend your right hand so that the fingers, thumb, and palm form a flat surface with the thumb at right angles to the fingers. Align the thumb along the conductor pointing in the direction of the current and the fingers pointing in the direction of the magnetic field (from the magnet) that is passing the conductor. The palm, then, is facing in the direction of the force that the field from the magnet exerts on the conductor (see Figure 14.29).

The magnetic field of the magnet points away from the N-pole of the magnet past the conductor. If the conductor were an ordinary magnet, its N-pole would experience a force directly away from the magnet (to the right). But the conductor has no N-pole or S-pole. Instead, the magnetic field from the magnet exerts a force at right angles to both the direction of the current and the direction of the magnet's field. Notice that all three directions (the current, the field, and the force) are all at right angles to each other (mutually perpendicular). It's easy to remember how to apply the rule if you think of the thumb, the fingers, and then the palm. There is one current (the thumb) passing through many lines of force (the fingers) and (the palm) "pushes" in the direction of the force on the conductor (Figure 14.29). This phenomenon is called the **motor effect** since it is the driving force that makes electric motors run.

At this point, it is important to realize that if the current crosses the field at an oblique angle, rather than at right angles, you must identify the direction of the component of the magnetic field that lies perpendicular to the current in order to apply right-hand rule #3. If the direction of the magnetic field is parallel to the current, then there is no component of the field perpendicular to the current, and as a result there is no force exerted by the field on the conductor.

Figure 14.29 A conductor that carries a current at right angles to a magnetic field experiences a force at right angles to both the current and the direction of the field. This direction can be predicted by using right-hand rule #3.



INVESTIGATION 14-E

The Motor Effect

TARGET SKILLS
- Predicting
- Modelling concepts

When a current passes at right angles through a magnetic field, Field theory predicts that the current (and thus the conductor that carries it) experiences a force at right angles to both the direction of the current and the field through which it is passing.

Problem

In this investigation, you will determine if that force exists and if the direction of the force is correctly predicted by right-hand rule #3.

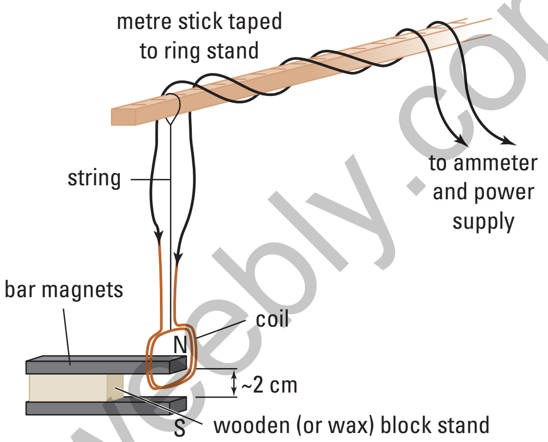
Equipment

- bar magnets (2) or a horseshoe magnet
- wire (about 2 metres long to make a coil)
- power supply
- ammeter (0 to 10 A)
- resistor ($\approx$1 Ω, exact value is not important)
- retort stand (2)
- ring clamp
- string
- wax block
- elastic bands

Part 1

Procedure

1. Wrap the two-metre segment of wire around a block that is about 2 cm × 2 cm to make a coil with at least 20 turns. Leave the ends about 10 cm long to connect the coil to the leads from the circuit.
2. Set up the apparatus as shown on the upper right. Suspend the coil so that its bottom edge is between the poles of the two bar magnets (or the horseshoe magnet) as shown.



3. Turn up the potential difference of the power supply very slightly to check that the meter is connected correctly.
4. Once the circuit is connected correctly, increase the potential difference (until a current of about 5 A is reached).
5. As the current is increased, observe the coil for movement.
6. Draw a sketch showing the direction of the current, the magnetic field from the magnet, and the direction of movement.
7. Apply right-hand rule #3 to see if the movement that was observed was in the direction of the predicted force.
8. Reverse the direction of the magnetic field. Repeat steps 4 through 7.
9. Reverse the direction of the current in the coil. Repeat steps 4 through 7.

continued ▶

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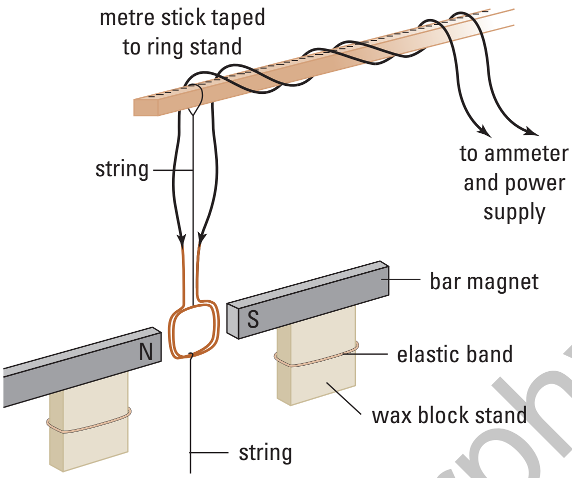
Part 2

Procedure

1. Position the magnets so that both edges of the coil are between the poles of the magnet as shown below. If you attach a string to the bottom of the coil, as shown in the diagram, and hold it gently down, it will stabilize the motion of coil so that the motion caused by the field is easier to observe.



2. Increase the potential difference of the power supply to about 5 A (or to a current that provided observable results during Part 1).
3. Observe the reaction of the coil to the field.
4. Draw an accurate sketch of the motion of the coil with respect to the direction of the field. Make sure you include the directions of the current and the magnetic field, as well as the forces experienced by the coil.
5. Apply right-hand rule #3 to the system to determine if the observed reaction of the coil could be predicted.
6. Reverse the direction of the magnetic field. Repeat steps 2 to 5.
7. Reverse the direction of the current in the coil. Repeat steps 2 to 5.

Analyze and Conclude

1. In Part 1, did right-hand rule #3 correctly predict the movement of the coil when the current was (a) perpendicular, (b) oblique, and (c) parallel to the field?
2. In Part 1, did any unexpected movement of the coil occur? Try to explain these movements, if any.
3. Answer the following questions about Part 2:
   (a) Explain why the coil moves as it does? Why does it stop moving where it does?
   (b) Does right-hand rule #3 correctly predict the motion of the coil?
   (c) Apply right-hand rule #3 to the top and bottom edges of the coil. Does the rule predict that these edges experience a force? Explain why the coil does not seem to respond to the forces on the top and bottom edges of the coil.

Apply and Extend

4. Could the coil be made to move away from the position it took up when the current was first turned on? Explain how this could happen.

UNIT PROJECT PREP

Motors rely on the interaction between electricity and magnetism.

- How important is magnetic field strength to motor design?
- How does the shape of the conductor in the magnetic field affect its operation?

Defining the ampere

On September 4, 1820, Ampère read an account of Oersted's discovery of electromagnetism. On November 6th, he published his paper on electromagnetism which has become the basis for modern electromagnetic theory. In the paper, Ampère developed his famous mathematical law that describes the relationship between the current in a conductor and the magnetic field that results from it. In the paper Ampère also defined the unit of current, later named in his honour, and created the first "right-hand rule."

Ampère reasoned that if a current-carrying conductor created a magnetic field about itself, then two current-carrying conductors should interact by attracting or repelling each other in the same way as two magnets. To test this theory, he placed two conductors parallel and at a small distance from each other. He discovered that when the currents were in the same direction, the conductors attracted each other, and when currents were in the opposite direction, the conductors repelled each other.

Figure 14.30 shows two parallel conductors, A and B, carrying currents in the same direction. The lines of force (in blue) represent the magnetic field from conductor A. Right-hand rule #1 can be used to verify that, at the position of conductor B, these lines point vertically upward. Right-hand rule #3 can be used to verify that the direction of the magnetic force on the current in conductor B is toward conductor A.

PHYSICS FILE

André Marie Ampère (1775-1836) was known mainly for his genius in mathematics. He began to read books on mathematics at the age of 13, and by age 16, he was writing papers on various aspects of his studies. In 1804, even though he had never attended a university or earned a degree, he was invited to become a professor of mathematics at the École Polytechnique in Paris. Even though the majority of Ampère's work was in mathematics, the two months he spent on electromagnetism laid the groundwork for the application of mathematics to electromagnetism.

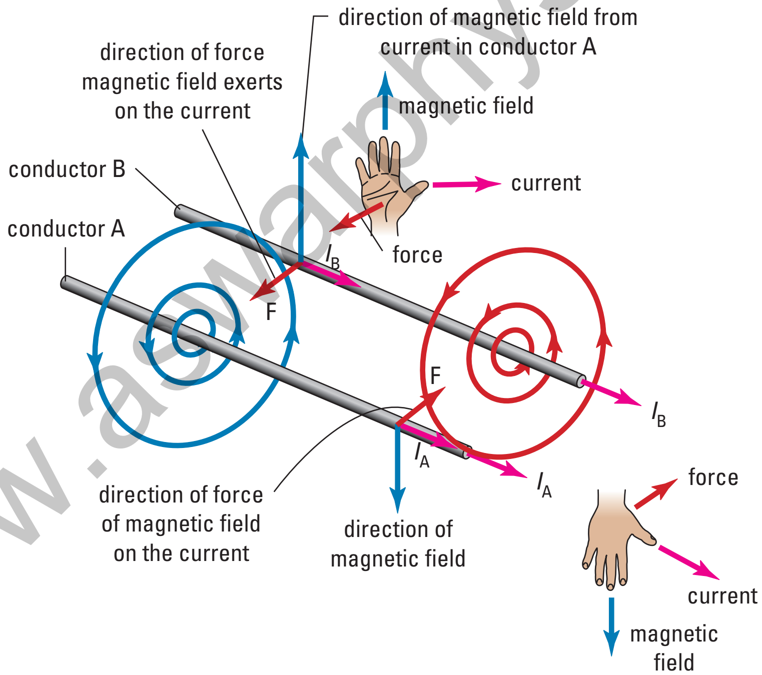
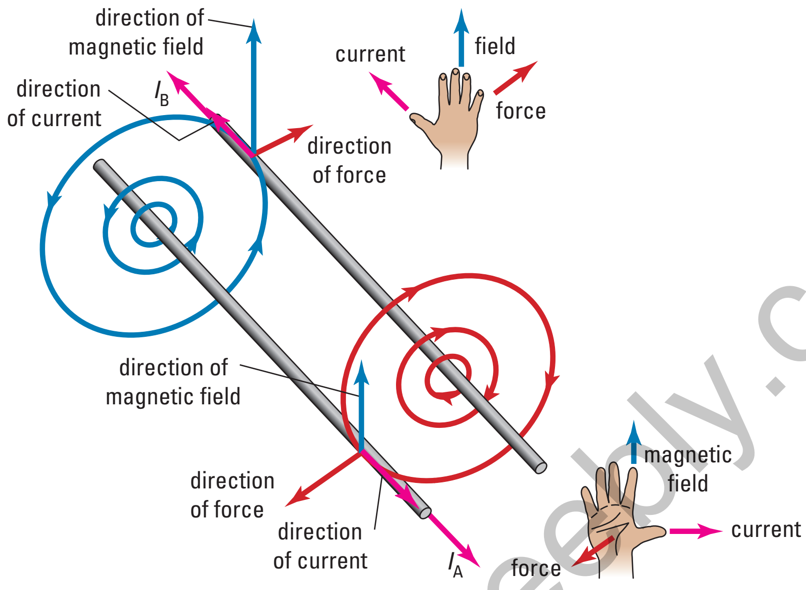


Figure 14.30 Parallel conductors carrying currents in the same direction experience a mutual force of attraction.

Figure 14.31 When parallel conductors carry currents in opposite directions, the magnetic forces cause the conductors to repel each other.



Similarly, the lines of force (in red) represent the magnetic field from the current in conductor B at the position of conductor A. As they pass conductor A, these lines of force point vertically downward. Right-hand rule #3 indicates that the magnetic force on the current in conductor A is toward conductor B. Therefore, the two conductors appear to be attracted to each other.

Figure 14.31 shows two parallel conductors, A and B, carrying currents in opposite directions. Applying right-hand rule #3, in the same way as shown in Figure 14.30, will reveal why these two conductors repel each other.

Ampère discovered that the force (F) between the current-carrying conductors varied directly as the current in conductor A ($F \propto I_A$), directly as the current in conductor B ($F \propto I_B$), directly as the length ($F \propto L$) of the parallel conductors, and inversely as the distance ($F \propto \frac{1}{d}$) between the conductors. These relationships can be written, as shown, in one relationship.

$$F \propto \frac{I_A I_B L}{d}$$

Multiplying the right side by a proportionality constant (K) produces the equation:

$$F = K\frac{I_A I_B L}{d}$$

The units for force (F), length (L) and distance (d) had been defined prior to Ampère's investigation. The unit for current had not been defined so Ampère could now choose a unit for electric current that would produce a proportionality constant of any desired value. For example, the unit of force (1 N) was chosen to be the force that would cause one unit of mass (1 kg) to accelerate at one unit of acceleration (1 m/s^2). Similarly, the unit of resistance (1Ω) was chosen so that one unit of potential difference (1 V) would cause one unit of current (1 A) to move through it.

Ampère did something that was unique in science. He chose the unit of current to be the current that, when flowing in each conductor, would cause the force of attraction or repulsion between the conductors to be exactly 2×10^{-7} newtons per metre of conductor. Because of this choice, the value of the proportionality constant is, by defintion, exactly 2×10^{-7} N/A^2. Had he chosen the current large enough to make $K = 1$, you would probably be more familiar with currents of milliamperes (mA) or microamperes (μA) rather than amperes (A).

One point that is often confusing to students of physics is the relationship between the unit of current and the unit of charge. Usually, current is defined in terms of the movement of a particular quantity per unit time. Water currents, for example, are often measured in litres per second. Therefore, it is often assumed that the unit of current (A) is defined in terms of the quantity of charge that moves per unit time, coulombs per second (C/s). But that is not the case; in fact the reverse is true. The unit of charge (one coulomb) is by definition the amount of charge that is moved by a current of one ampere in one second (1 C = 1 A·s).

Even though the coulomb is not a particularly large charge when viewed from the point of view of current electricity, it turns out that it is extremely large from the point of view of electrostatics. If you could place one coulomb of static electric charge on each of two bodies separated at a distance of one metre, they would exert an electrostatic force of about 9×10^9 N on each other.

PHYSICS FILE

Had Ampère decided that one unit of current (1 A) in two conductors of one unit length (1 m) separated by one unit of distance (1 m) would cause one unit of force (1 N) then the value of the proportionality constant would have been, by definition equal to one. But the force of interaction between two current-carrying conductors is very weak. To produce a force of one newton would have required a current much greater than Ampère's batteries could have produced.

The Motor Force: Quantitative Analysis

When a conductor carries a current through a magnetic field, several factors affect the size of the force exerted on the conductor. First, magnitude of the force (F) exerted varies directly as the magnitude of the magnetic field ($B_\perp$) that acts perpendicular to the conductor. Second, the magnitude of the force varies directly as the magnitude of the current (I). Third, the magnitude of the force varies directly as the length of the conductor inside the field (L). Mathematically, the above statements can be written as

$$F \propto B_\perp$$
$$F \propto I$$
$$F \propto L$$

Combined mathematically, they become

$$F \propto B_\perp IL$$
$$\therefore\ F = kB_\perp IL$$

where k is the proportionality constant.

When this relationship was first discovered, the units for all the quantities except magnetic field strength (B) had been defined. Thus, it was possible to define the **tesla**, the unit of magnetic field strength in terms of the force exerted on a current in the conductor. In this way, the value of k could be made equal to one (1). Rearranging in terms of the other variables, the magnetic field strength is:

$$B_{\perp} = \frac{F}{IL}$$

This equation shows the relationship between the magnitudes of the variables involved. To find the directions, you must apply right-hand rule #3. Notice that the equation only works for magnetic fields that are perpendicular to the current. In the next course, it will be extended to apply to situations in which the current is not perpendicular to the field.

If a coil with n (n) turns of wire passes through a field, then the length of conductor inside the field is found by taking the product of number of turns in the coil (n) and the length of an individual turn (ℓ). Therefore

$$L = n\ell$$

MAGNETIC FIELD STRENGTH AND MOTOR FORCE

The magnetic field strength perpendicular to the conductor is the quotient of the motor force and the current and length of the conductor.

$$B_{\perp} = \frac{F}{IL}$$

$$L = n\ell$$

Quantity	Symbol	SI unit
magnetic field strength	B	tesla (T)
"perpendicular to"	$\perp$	
motor force	F	newton (N)
current	I	amp (A)
length of conductor	L	metre (m)
number of coil turns	n	no unit
length of each turn	ℓ	metre (m)

Unit Analysis

By definition in the first formula, 1 tesla = $\dfrac{(1\ \text{newton})}{(1\ \text{amp})(1\ \text{metre})}$

$$\text{T} = \frac{\text{N}}{\text{A} \cdot \text{m}}$$

MODEL PROBLEM

Calculating Magnetic Field Strength

A length of straight conductor carries a current of 4.8 A into the page at right angles to a magnetic field. The length of the conductor that lies inside the magnetic field is 25 cm (0.25 m). If this conductor experiences a force of 0.60 N to the right, what is the magnetic field strength acting on the current?

Frame the Problem

- Since it is known that the current is at right angles to the field, the formula for magnetic field strength applies to this problem.
- Right-hand rule #3 can be used to find the direction of the field.

Identify the Goal

Find the strength (size and direction) of the magnetic field acting on the current.

Variables

Involved in the problem	Known	Unknown
F	$F = 0.60$ N	$B_{\perp}$
$B_{\perp}$	$I = 4.8$ A	
I	$L = 0.25$ m	
L		

PROBLEM TIPS

- Make sure you know that the *current* and the *magnetic field* act at right angles. This information may be given in many different ways in the problem statement so read very carefully.
- Convert the law from the standard form into the form required to solve the problem.
- It is always necessary to solve the direction portion of the problem separately from the calculation, using right-hand rule #3. You must always identify the directions for two of the three vectors (current, field, and force) to find the direction for the third.

Strategy

State the equation relating magnetic field strength to force, current and conductor length.

Substitute the known values into the equation.

A $\frac{\text{N}}{\text{A m}}$ is equivalent to a T.

Apply right-hand rule #3 to find the direction of the magnetic field.

The magnetic field strength is 0.50 T upward.

Calculations

$$B_{\perp} = \frac{F}{IL}$$

$$B_{\perp} = \frac{0.60 \text{ N}}{(4.8 \text{ A})(0.25 \text{ m})}$$

$$B_{\perp} = 0.50 \text{ T}$$

Hold up your right hand with your thumb pointing into the page (away from you). The palm of your hand must face the right hand side of the page (the direction of the force). Then your fingers are pointing in the direction of the field.

continued ►

continued from previous page

PRACTICE PROBLEMS

1. A magnetic field has a strength of 1.2 T into the page. A current of 7.5 A flows vertically upward through a conductor that has 0.080 m inside the field. Find the force that the field exerts on the conductor.

2. A coil that consists of 250 turns of wire has an edge 12 cm long that carries a current of 1.6 A to the right. If the edge of the coil is inside a magnetic field of 0.16 T pointing out of the page, what is the force the field exerts on the coil?

3. A coil, consisting of 500 (5.00×10^2) turns of wire has an edge that is 3.60 cm long that passes at a perpendicular angle through a magnetic field of 0.0940 T into the page. If the magnetic force on the edge of the coil is 10.8 N to the right, what was the current through the coil?

4. What magnetic field will exert a force of 22.0 N downward on a coil of 450 turns carrying a current of 3.20 A to the right through the field? The edge of the coil inside the field is 7.50 cm long.

Torque on a Coil

In Part two of Investigation 14-E, you observed the effect on a coil when two edges were inside the magnetic field. The result was that the coil twisted in the field. The currents in the edges of the coil experience forces in the opposite direction. (right-hand rule #3) These forces create a **torque** (just like a magnetic dipole) about the axis of the coil. If the coil is free to move, the torque will reorient the coil so that its plane is perpendicular to the field. Once the plane of the coil is perpendicular to the field, the forces on the edges of the coil are linearly opposed so that the net force on the coil is zero.

Notice that the coil is now oriented so that the magnetic field due to the current through the coil (use right-hand rule #2) is in exactly the same direction as the field from the magnets. Placing an iron core inside the coil greatly increases the strength of the magnetic field from the current, and thus greatly increases the torque on the coil.

The DC Electric Motor

You now have all the elements (in theory, at least) to build an electric motor. The motor has a coil with an iron core, called the **rotor** or **armature**, surrounded by field magnets. In many motors, the field magnets are electromagnets.

There are two obvious difficulties in electric motor design. First, when the coil turns so the magnetic forces on the edges of the coil are aligned directly opposite each other, it will no longer experience any torque. If you could now reverse the direction of the current, and thus the direction of forces, they would point inward,

ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner for a short animation about the use of electromagnets and permanent magnets in an electric motor.

rather than outward, and the edges of the coil would again experience a torque. Second, if the coil keeps turning, the leads to the coil will eventually become so twisted they will break.

The solution to both of these problems was solved by one device called a **split ring commutator**. The split ring commutator, as its name implies, is a brass or copper ring cut into two halves. The commutator is attached to the axle of the armature so that it rotates with the coil. One end of the coil is connected to each half of the commutator. Brushes (either metal or carbon) slide on the commutator to pass current from the battery to the coil. At this point, the coil can turn freely without twisting the leads to the coil. Even though a direct current comes from the battery, as the armature rotates, the brushes pass from one segment of the commutator to the other. When the brushes change contact from one half of the commutator to the other, the direction of the current in the coil is reversed. If this occurs at the instant when the coil has reached the point where its plane is perpendicular to the field, the forces on the edge of the coil will reverse and continue to cause the coil to continue its rotation through the field (see Figure 14.32).

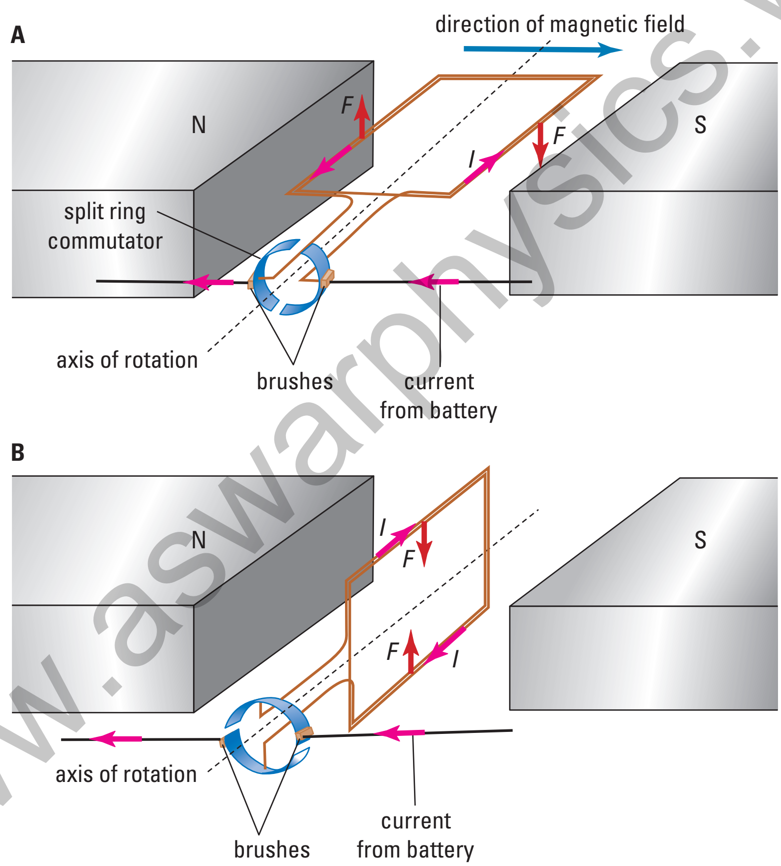
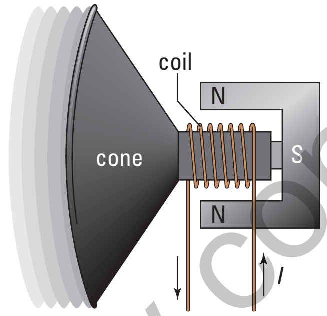


Figure 14.32 **(A)** When the plane of the coil is parallel to the magnetic field, the torque on the coil is at a maximum. **(B)** When the plane of the coil is perpendicular to the field, the torque is at a minimum. At that point, the brushes cross over to the other segment of the commutator, reversing the current in and the forces on the edges of the coil.

PHYSICS FILE



When a current flows through the coil of the loudspeaker, the magnetic field from the coil interacts with the field from the field magnet surrounding the coil. The current that the amplifier sends to the coil varies in strength so that the coil experiences a varying force, pushing it back and forward along its axis. Thus, the cone of the speaker moves back and forth in the same pattern as the fluctuations in the current, setting up a pressure wave that you hear as sound.

CANADIANS IN PHYSICS

The Skeleton's Name is George.

Dr. Zahra Moussavi, biomedical engineer.

Due to revolution and war, universities in Iran were closed in 1978. As a result, it took Zahra Moussavi nine years to complete a four-year BSc in electronic engineering. In 1989, Zahra and her family moved to Canada. She obtained an MSc from University of Calgary and a PhD from the University of Manitoba. Today, Dr. Moussavi teaches biomedical engineering and does research at the University of Manitoba. With the help of George, she studies the movement of arms and shoulders. Her research will help physicians decide how well a surgery has worked and the nature of the post-surgical rehabilitation that may be required.

Many patients, as the result of a stroke or brain tumour, have difficulty swallowing. Current techniques for detecting abnormalities are inadequate.

Dr. Moussavi is exploring the use of accelerometers as a method of detecting the sounds of swallowing and breathing. This technique has already proven valuable in the analysis of injuries to joints such as knees.

14.4 Section Review

1. C Two materials, A and B, both exhibit strong magnetic attraction when they are brought near a magnet. When the magnet is removed, material A loses its magnetism but material B retains its magnetism. Using domains, explain what happens with the two materials.

2. K/U A magnetic field points directly into the page. A square coil is inside the field so that the plane of the coil is parallel to the surface of the page. From your perspective, looking at the page, the current moves counter-clockwise around the coil. Find the direction of the force on each edge of the coil.

3. K/U A square coil lies in the plane of the page. The current flows in a clockwise direction inside the coil. If the magnetic field is to the right, identify the direction of the force on each edge of the coil.

4. K/U A square coil lies so that its plane is horizontal; two of its edges are parallel to the page and two of its edges are perpendicular to the page. If the magnetic field surrounding the coil points out of the page, in which direction will the coil experience a torque if the current is flowing into the page through the left-hand edge of the coil?

UNIT PROJECT PREP

To improve your motor design, think about the fundamental principles of magnets and motors.

- What is the motor effect?
- Why do current-carrying conductors react to magnetic fields?

CHAPTER 14 Review

REFLECTING ON CHAPTER 14

- Magnets are always found as a dipole with both an N-pole and an S-pole. Breaking a magnet into two parts results in each part being a dipole.
- For magnetic poles, like poles repel each other while unlike pole attract. The force of attraction or repulsion varies inversely as the square of the separation of the poles.
- Materials are classified according to their magnetic behaviour. The three most common classifications are ferromagnetic, paramagnetic and diamagnetic materials.
- Domain theory is used to explain why ferromagnetic materials can be induced to display magnetic behaviour.
- Faraday invented the Field theory to explain magnetism. It postulates that it is the magnet's field rather than the magnet itself that exerts the magnetic force. The field can be represented graphically by a "lines of force" diagram.
- Lines of force are continuous loops. The point on a ferromagnetic material where the lines of force exit is an N-pole and the point where the lines of force enter the material is an S-pole.
- The relationships between the directions of electric currents and magnetic fields are defined by the right-hand rules.
- Oersted discovered the existence of magnetic fields near a current-carrying conductor. A right-hand rule is used to determine the direction of the field relative to the direction of the current.
- Ampère developed the laws describing the force exerted on a current carrying-conductor by the magnetic field in which it is located. He used the magnetic force exerted between parallel current-carrying conductors to define the ampere.
- The motor effect states that when a current passes through a magnetic field at right angles to the field, the magnetic field exerts a force on the current at right angles to both the current and the field. The direction of the motor force is found using a right-hand rule.
- Electric motors use a split-ring commutator to convert the DC current from the battery to an AC current so that the coil on the armature would always experience a force driving it in the same direction. The forces exerted on the opposite edges of the coil are in opposite directions. This results in a twisting action or torque on the coil.

Knowledge/Understanding

1. Distinguish between the following:
   (a) the geographic North Pole and the magnetic north pole.
   (b) a compass needle and a dipping needle.
   (c) ferromagnetic, paramagnetic and diamagnetic materials.
   (d) lines of force and magnetic force.
2. Describe how magnetism is induced in a ferromagnetic material. Use references to domain theory in your explanation.
3. Describe what is meant by the magnetosphere. What is its role in creating the aurora borealis? Why are the auroras found in the polar rather than the equatorial regions of the magnetosphere?
4. Describe the two ways to use right hand rules to find the direction of the magnetic field inside a loop of wire.
5. Describe how the strength of a magnetic field is indicated in a line of force diagram.
6. A Compass needle is placed at the centre of a loop of wire. When a strong current is passed through the loop, the compass needle shows no change in position. What can you state about the orientation of the loop and the direction of the current through the loop?
7. A conductor lies in an east-to-west orientation across a table. Assume that the lines of force for Earth's magnetic field point due north across the conductor, and that two compasses are

placed so that one is above and the other is below the conductor. When the circuit is closed, a very strong electric current moves from west to east through the conductor. Use the right-hand rule to analyze what you should observe in the compass needles and why.

8. A conductor lies parallel to the lines of force from the Earth's magnetic field. A compass lies on top of the conductor so that its needle lies parallel to the conductor. As the current in the conductor is gradually increased, the compass needle gradually deflects to the west. (a) Is the current flowing north or south through the conductor? Explain. (b) At what angle would the compass needle be deflected when the magnetic field from the current is equal in magnitude to the Earth's magnetic field? Explain.

9. A solenoid is set up so that its axis is parallel to Earth's magnetic lines of force. A compass is placed at the geographic south end of the solenoid so that the N-pole of the compass points into the solenoid. When the current is turned on, the needle makes a 180˚ reversal in direction. Assume you are looking through the coil from its north end (due south along the axis of the coil). From your point of view, is the current moving around the coil in a clockwise or counter-clockwise direction? Explain your answer.

Inquiry

10. Design and build a solenoid. Wrap about 200 tightly wound smooth turns of wire around a cardboard tube. The core of a roll of toilet paper or paper towel works well as a supporting structure. Keep the turns so that they are wound around a section of only 8 cm to 10 cm in length. Connect the solenoid, in series, to a variable voltage power supply, an ammeter and a resistor of about 1.0 Ω.

(a) Increase the current to about 1.0 A. Use a compass trace a line of force from one end of the solenoid to the other. Refer to the technique used to trace lines of force in Investigation 14-B.

(b) Place a soft iron rod so that its end is just inside the end of the solenoid. Increase the current to about 4.0 A. Why does the rod move into the solenoid? (HINT: Consider the induced magnetic polarity of the rod and the strength of the magnetic field of the solenoid at the poles of the rod.)

11. Design and build an electromagnet that, when powered by a single D-cell (flashlight battery), will support at least 2.0 kg. Connect your electromagnet to a variable voltage power supply and an ammeter. Make a graph of the weight your magnet can support versus the current. Does the strength of the electromagnet increase in direct proportion to the current? From your graph predict whether the magnet has an upper limit for the load it can support. Explain.

Communication

12. Describe how Domain theory explains the difference between a permanent and a temporary magnet.

13. Contrast how the Action-at-a-distance theory and Field theory explain how a compass indicates directions on the Earth.

14. Describe the significance of Gilbert's spherical lodestone.

15. The table (Table 14.1) on page 673 gives the Curie point of gadolinium as 16˚ C. What does this mean for the magnetic properties of this material?

16. The two statements "like poles repel" and "unlike poles attract" are throwbacks to the Action-at-a-distance theory in that they imply the two poles interact with each other directly. Rewrite these two statements to reflect a Field theory perspective.

17. Explain how to apply a right-hand rule(s) to determine whether the force one long straight conductor exerts on a second conductor that runs parallel to it is an attractive or a repulsive force.

18. Draw a circular loop of wire that lies in the plane of the page. Draw an arrow to indicate that the current in the loop flows in the counter-clockwise direction. Draw "dots" and "crosses" to indicate the lines of force magnetic field inside and outside the loop as they pass through the plane of the page.

19. A solenoid lies in the plane of the page with its axis parallel to the edge of the page. The magnetic lines of force flow through the loop towards the bottom of the page. Draw a diagram of the solenoid, showing windings and the direction of the current through the windings.

20. A simple electric meter can be made by placing a compass at the centre of a coil of wire. How should the coil and compass be aligned so that the deflection of the compass can be used to indicate the size and direction of the current in the coil? Explain how this system could be used to indicate the size of the current.

21. Describe the role of the commutator in a DC motor. Support your description with diagrams to illustrate the function of the commutator.

22. A coil of wire, which is free to turn, is suspended so that its plane is parallel to Earth's magnetic field. When a current flows in the coil, it turns so that its plane is perpendicular to Earth's magnetic field. Explain why this happens.

Making Connections

23. The solenoid is often described as a linear motor. If a rod is placed so that one of its ends is in a solenoid, the magnetic field of the solenoid will draw the rod into the solenoid (See Question 10). This action is employed in many industrial and home appliances. Prepare a list of the devices in the home that use solenoids. For each device, describe the purpose of the solenoid.

24. Investigate and report on the method by which information is recorded on a magnetic audio or video tape or a computer disk.

25. When you board an aircraft you are not allowed to use certain electronic devices during take off and landing. Investigate and report on which devices are not to be used and why this is so.

26. The Earth's magnetosphere at its most basic level is the reason why we can use magnetic compasses to navigate. However, its existence has many other important implications to our lives. Investigate and report on the importance of the magnetosphere to life on Earth.

Problems for Understanding

27. Changes in magnetic field strength are shown by increasing or decreasing the number of lines. What can you deduce from a sketch showing one magnet with five times as many magnetic lines as another magnet?

28. Magnetic north continually, although slowly, changes position. Calculate the average speed with which magnetic north moves, if it moved 254 km over a 143 year period.

29. A hiker checks her compass and orients herself so that she is facing exactly north according to her compass. She then checks her map of isogonic lines and discovers that magnetic north deviates by exactly 22.0˚ West of the geographic North Pole.

(a) By how many degrees and in what direction should she change her orientation so that she is facing directly at geographic North Pole?

(b) By how many degrees and in what direction should she change her orientation so that she is facing directly east of the geographic North Pole?

30. Two parallel conductors carry current in opposite directions as shown in Figure 14.50. Describe the change in magnitude of the force for each of the following scenarios.

(a) The current in one conductor is doubled.

(b) The current in both conductors is tripled.

(c) The distance between the conductors is halved.

Numerical Answers to Practice Problems

1. 0.72 N[left] **2.** 7.7 N[down] **3.** 6.33 A[down]
4. 0.204 T[out of page]

CHAPTER 15 Electromagnetic Induction

CHAPTER CONTENTS

Hydroelectric dams, like the one at Churchill Falls in Labrador, generate electrical power by using the potential energy of the water stored in the dam's reservoir to drive massive electric generators.

Until Faraday discovered electromagnetic induction, the only source of current electricity was from the chemical action of batteries. Generators, such as the ones in the photograph, convert mechanical energy into electrical energy at rates that would have been impossible using batteries. The Churchill Falls hydroelectric station, completed in 1971, can produce electrical energy at a rate of over 6500 megawatts (MW), with plans to add another 3200 MW by the end of the year 2006.

In this chapter, you will extend your understanding of electromagnetism to include electromagnetic induction and the various ways it is used in generators and transformers.

INVESTIGATION 15-A

Faraday's Discovery

TARGET SKILLS
- Analyzing and interpreting
- Performing and recording

When Oersted discovered that an electric current produced magnetic effects, Faraday hypothesized that the reverse might also be true. To test his theory, he constructed a device similar to the one shown in the diagram. Faraday reasoned that when the battery caused the iron bar to become an electromagnet, the magnetic field would induce a current that would be detected by the galvanometer. In this investigation you will discover if Faraday was correct.

Problem

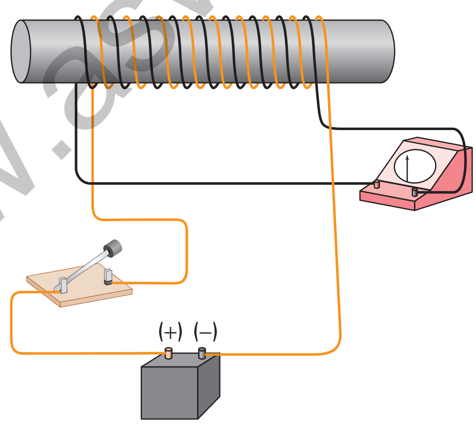
Under what circumstances does a magnetic field induce an electric current?

Hypothesis

When the switch is closed in the apparatus shown below, how do you expect the galvanometer to react, and why?

Equipment

- iron rod (about 10 cm long)
- two 2 m lengths of insulated copper wire
- 6.0 V lantern battery
- switch
- galvanometer
- five alligator clip leads
- masking tape



Procedure

1. Wind the iron rod with at least 50 turns of wire. Leave lengths of wire at each end of the coil to make connections. Wind a second coil of at least 50 turns of wire over the top of the first coil as shown in the diagram. A little masking tape can be used to make sure the coils do not unwind. Connect one coil to a battery with a switch, *keeping the switch open*. Connect the other coil to a galvanometer.

CAUTION The circuit to which the battery is connected is a short circuit. Leave the switch closed only long enough to confirm your observations in the next steps. Avoid touching connections while the switch is closed.

2. Close the switch for a second or two to complete the circuit of the coil connected to the battery. Does a current flow through the galvanometer when there is a current in the coil connected to the battery? If so, how long does the current last? Close and open the switch a few times to verify your observations.

Analyze and Conclude

1. When a current is flowing in the coil connected to the battery, is there a current in the coil connected to the galvanometer?
2. Did the galvanometer react at any time to the current in the coil connected to the battery? If so, when and how?
3. Is the *direction* of the current in the galvanometer affected by the current in the coil connected to the battery?
4. Adjust the connection of the coil connected to the battery so that the current in the coil is reversed. Does this affect the reaction of the galvanometer? If so, describe the effect.
5. What conclusion can you make regarding a magnetic field's ability to induce an electric current in the coil connected to the galvanometer?

15.1 The Generator Effect

SECTION EXPECTATIONS

- Analyze and describe electromagnetic induction in quantitative terms.
- Analyze and predict the behaviour of induced currents using the right-hand rules.
- Hypothesize and test qualitative effects of electromagnetic induction.
- Explain the factors that affect the force on a current carrying conductor in a magnetic field.

KEY TERMS

- generator effect
- electromagnetic induction
- AC generator
- slip-ring commutator
- DC generator
- rectified DC current
- alternator

Technology Link

Electric current is produced in microphones in three different ways. Dynamic microphones produce electricity using electromagnetic induction. Ceramic microphones use piezoelectric crystals to produce tiny electric currents. When sound waves move, the microphone diaphragm pressure is exerted on the piezoelectric crystals inside, causing them to produce electricity. The third type of microphone, the condenser microphone, uses a variable capacitor to create the fluctuations in current. Find out which types of microphone are typically used in the recording industry.

Figure 15.1 Microphones use sound to induce an electric signal.

Microphones are just one of the thousands of devices that convert mechanical energy to electrical energy. In the most common type of microphone, sound waves striking the diaphragm of the microphone cause a tiny coil to move inside a magnetic field. This movement induces the currents that are sent to the amplifier.

Currents from Magnetic Fields

In 1820, Ampère had shown that an electric current produces a steady magnetic field. In 1831, Faraday read of Ampère's findings and, by the principle of symmetry, predicted that a steady magnetic field should produce an electric current. The first few attempts to verify his hypothesis produced no results. On his sixth attempt, his investigations produced a rather surprising result.

On one side of an iron ring, he wound a wire solenoid that he connected to a battery and a switch. On the other side, he wound a wire solenoid that he connected to a galvanometer (Figure 15.2). Faraday thought that when he closed the switch, the current through the first solenoid would create a set of magnetic lines of force that would permeate the iron ring. These magnetic lines of force flowing through the second solenoid would cause a current that could be detected by the galvanometer.

When Faraday closed the switch, the needle on the galvanometer deflected to show a current, and then, unexpectedly, quickly dropped back to zero. As long as the switch was closed, the current remained at zero. Faraday could easily demonstrate that as long as the switch was closed, there was a magnetic field inside the ring. However, there was no accompanying current in the second solenoid. When he opened the switch, the needle on the galvanometer was again momentarily deflected, but in the opposite direction, indicating that for a brief time a current flowed in the opposite direction.

Faraday realized that a *steady* magnetic field through the ring would not generate the desired induced current. The brief pulses of current in the second solenoid, he hypothesized, must have been the result of the fluctuation in the strength of the magnetic field that occurred when the current was turned on or off.

Once again, the power of Faraday's field theory becomes evident. Faraday reasoned that when he turned the current on, the magnetic field inside the ring grew in strength. As the magnetic field grew, its lines of force expanded outward to fill space around the ring. As the lines of force expanded outward, they moved over the coils of the second solenoid. He argued that it was the motion of the lines of force across the coils that induced the current in the second solenoid.

Once the current was established in the first solenoid, the size of the magnetic field around the ring became constant. Since the lines of force were no longer changing, no current was induced in the second solenoid. However, when the current was turned off, the magnetic field collapsed. The lines of force now moved inward across the coils of the second solenoid, causing a brief current in the opposite direction.

To test his hypothesis, Faraday tried moving a magnetic field (from a bar magnet) into and out of a coil of wire. Just as he predicted, the movement of the magnetic field in the vicinity of the coil induced a current in the coil, as long as the magnet was moving. When the motion of the magnet stopped, so did the current. The direction of the induced current was dependent on the *relative motion* of the coil with respect to the magnet (Figure 15.3). Faraday had discovered the **generator effect**: the motion of magnetic lines of force past a conductor induces a current in the conductor. The process of generating an electric current in this way is now known as **electromagnetic induction**.

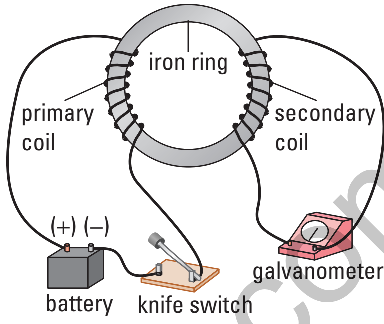


Figure 15.2 Faraday used an iron ring wound with two solenoids to test whether the magnetic field from one solenoid could induce a current in the second solenoid.

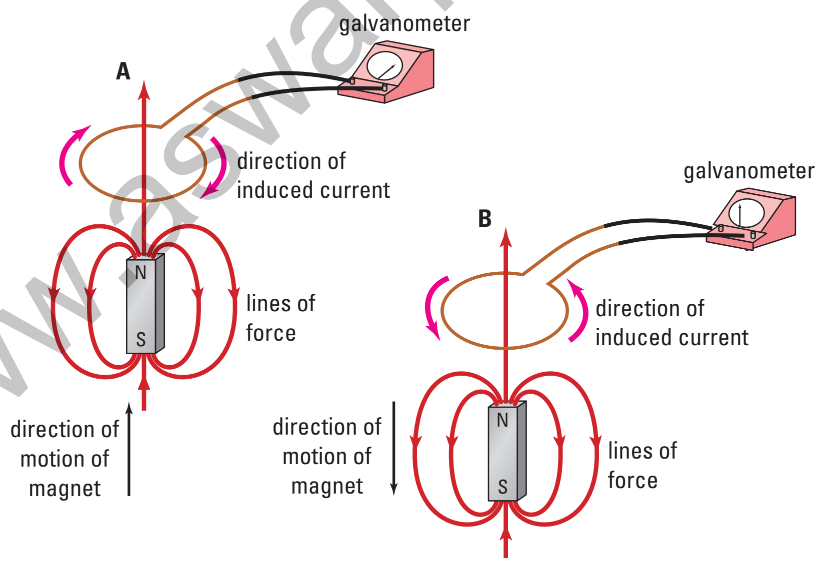


Figure 15.3 The motion of magnetic lines of force past a conductor can induce a current in the conductor. The direction of the current depends on the relative motion of the coil with respect to the lines of force.

INVESTIGATION 15-B

Induced Currents

TARGET SKILLS
- Identifying variables
- Performing and recording
- Communicating results

When a conductor is moved inside a magnetic field, an electric current is induced in the conductor. It would seem natural to assume that the properties of the motion (speed, direction, and orientation) would affect the size and direction of the current. Other possible factors that might affect the induced current are the strength of the field and the length of the conductor inside the field.

In this investigation, you will try to determine, qualitatively, the relationship between the induced current in the coil and the factors that might affect that current.

Problem

Determine a qualitative relationship between the induced current and (a) the motion of the coil, (b) the strength of the magnetic field, and (c) the length of the conductor.

Prediction

For each part of the investigation, make a prediction and record it in your logbook.

Part 1

Predict how the speed of the coil (a) perpendicular to the field and (b) parallel to the field will affect the reading on the galvanometer.

Part 2

Predict the effect of the strength of the magnetic field on the reading of the galvanometer.

Part 3

Predict the effect of the length of the conductor that moves in the field on the reading on the galvanometer.

Equipment

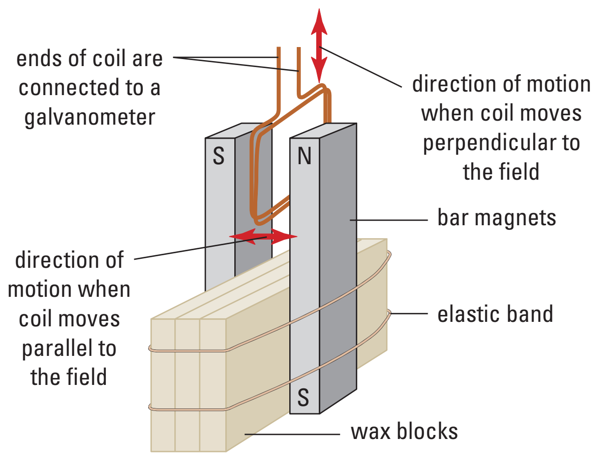
- bar magnets (6)
- wax blocks
- elastic bands
- copper coil (5 turns, 2 cm × 2 cm square)
- copper coil (10 turns, 2 cm × 2 cm square)
- copper coil (20 turns, 2 cm × 2 cm square)
- alligator clip leads
- galvanometer

Procedure

Note: It is important that you make careful observations as you proceed through each part of this investigation. The observations you make in Part 1 will affect what you do in Part 2.

Part 1

1. Set up the magnets on the wax blocks with one pair of magnets mounted on them so that the N-pole of one magnet is about three centimetres from and facing the S-pole of the other magnet.
2. Using the coil with 20 turns, move the coil so that one edge of the coil moves across the magnetic field at right angles to the field between the magnets (see below).



3. Observe the motion of the galvanometer needle. In a table, like the one shown below, record your observations of the reaction (both direction and magnitude) of the galvanometer needle. Try to use consistent slow and fast speeds.

Direction of motion	Speed of motion	Galvanometer reading (size and direction)
1. Perpendicular to field, inward	slow	
2. Perpendicular to field, outward	slow	
3. Perpendicular to field, inward	fast	
4. Perpendicular to field, outward	fast	
5. Parallel to field, N- pole to S-pole	slow	
6. Parallel to field, S-pole to N-pole	slow	
7. Parallel to field, N-pole to S-pole	fast	
8. Parallel to field, S-pole to N-pole	fast	

Part 2

1. Note that the actual length of the conductor inside the field depends on the number of turns of wire that form the coil. Thus the effective length of wire for the coil with 10 turns is twice that of the coil with 5 turns.

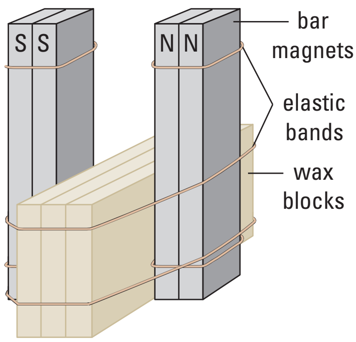
2. Examine the response of the galvanometer to each of the tests you did in Part 1. Using your observations from Part 1, move each of the coils, in turn, through the field in directions that had significant responses. (For example, if both perpendicular and parallel motions affected the current in the coil, then continue to test the effect of both of these motions throughout the experiment.)

3. Try to make the speed of all the coils as consistent as you can as you move them through the field. Observe the reaction of the galvanometer for each of the trials you perform, and record your observations in a table like the one below.

Direction of movement of the coil	Number of turns	Galvanometer reading (size and direction)

Part 3

1. To test the effect the strength of the magnetic field has on the induced current, the number of magnets used to create the field will be increased. Use elastic bands to hold two bar magnets with "like" poles together. Position two sets of these magnets so that they are aligned with the N-poles of one facing the S-poles of the other. Make sure that the gap between the poles is the same as in the previous trials (see the diagram below).



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2. Move the coil with 20 turns within the gap between the magnets, using the same orientations as in Part 2. Try to keep the speeds and orientations of the coils as constant as possible between trials. Record your observations in a table similar to the one below.

Direction of movement of the coil	Number of magnets	Galvanometer reading (size and direction)

3. Now, use an elastic band to hold three magnets together, just as you did in step 1 of this part of the investigation, and repeat step 2.
4. Use one magnet only on each side of the field, and repeat step 2.

Analyze and Conclude

1. How did moving the coil (a) perpendicularly to the field, and (b) parallel to the field affect the induced current?
2. How did the speed of the coil affect the induced current?
3. How did the length of the conductor (number of turns) affect the induced current?
4. How did the strength of the magnetic field affect the induced current in the coil? (**Note:** Do not assume that the field from two pairs of magnets doubles the field strength.)
5. In summary, briefly describe the factors that affect the strength and direction of the induced current in a conductor moving through a magnetic field.

PHYSICS & SOCIETY

TARGET SKILLS

- **Conducting research**
- **Communicating results**

Jillian was diagnosed with a brain tumour at age four. While most of the tumour could be removed by surgery, some of it was too deeply imbedded in her brain stem for removal. The doctors decided that they would need to monitor these cells for any sign of growth.

X-rays do not produce good detailed images of soft tissues. Instead, magnetic resonance imaging (MRI) is used. An MRI machine is just a large doughnut-shaped electromagnet. The nuclei of the hydrogen molecules in our tissues act like tiny magnets and become aligned with the magnetic field of the MRI machine. When these nuclei are subjected to low-energy radio waves, they are nudged out of alignment. When the radio waves are turned off, the nuclei snap back into alignment and give off a tiny electromagnetic pulse. Computer analysis transforms these pulses into detailed images of the tissue. Each image is a thin cross-section, so a series of these cross-sections creates a three-dimensional picture. Images show that, over the years, Jillian's tumour has not grown.

Going Further

Medical imaging methods include MRI, fluoroscopy, CT scans, ultrasound, and fibre-optics. Investigate these techniques and their uses.

Right-hand Rules for the Generator Effect

The generator effect can be explained in terms of the motor effect. Consider a conductor in the form of a straight rod, connected to a galvanometer, oriented in a magnetic field so that the rod is at right angles to the lines of force. Now, move the conductor so that it moves through the magnetic field in a direction perpendicular to both the lines of force and the orientation of the rod (Figure 15.4).

To find the direction of the induced current, Faraday devised a method using the right-hand rule in the same way as in the motor effect. He assumed that as the conducting rod moves upward through the field, each positive charge in the rod can be considered as a tiny bit of a current that is moving in the direction of the motion of the rod. Thus, by the motor effect, each charge moving within the conductor experiences a force (***F***) that acts at right angles to both the direction of the velocity (***v***) of the rod carrying the charges, and the lines of force of the magnetic field (***B***). In Figure 15.4, the magnetic field points into the page as the rod moves upward through the page. According to the right-hand rule, the direction of the force on the positive charges in the rod, and thus the current that is induced in the rod, is from right to left.

This application of the right-hand rule can be used to find the direction of the induced current in the coil as it moves through a magnetic field. In Figure 15.3(a) on page 719, the magnet is being moved upward toward the coil. As it approaches the coil, the lines of force curling outward from the magnet cut across the conductor.

To apply the right-hand rule, Faraday had to assume instead, that the conductor was moving downward toward the field. As the lines of force from the magnet loop around from the N-pole to the S-pole, the coil passes through the field so that the coil cuts across the lines of force. The detail in Figure 15.5 on the next page shows the direction of the motion of the coil, the direction of the lines of

ELECTRONIC LEARNING PARTNER

Go to your Electronic Learning Partner for an interactive activity on electromagnetic induction.

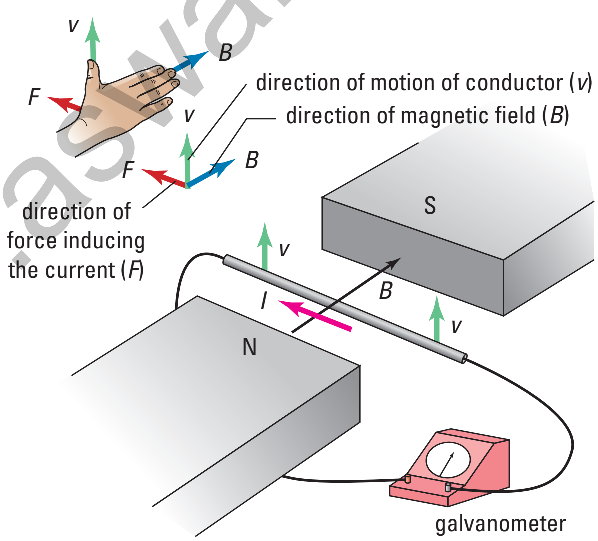


Figure 15.4 The charges in a moving conductor experience a force that pushes them along the length of the conductor to induce a current. The right-hand rule can be used to find the direction of the force on the charges that form the induced current.

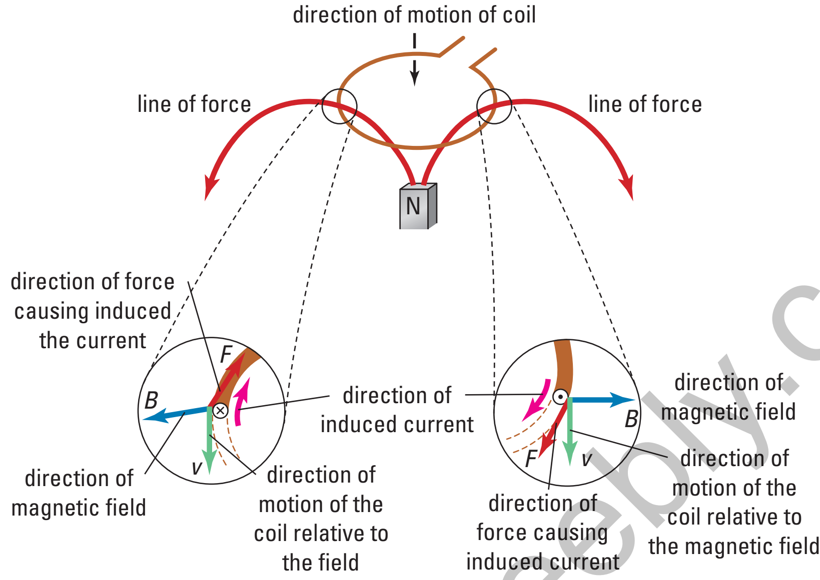


Figure 15.5 To use the right-hand rule to find the direction of the current induced in a conductor, the motion of the conductor with respect to the magnetic field must be identified.

force, and the direction of the resulting force that causes the induced current. On the right edge of the coil, the direction of the force (induced current) is out of the page. If viewed from above, the current in the coil would be flowing clockwise.

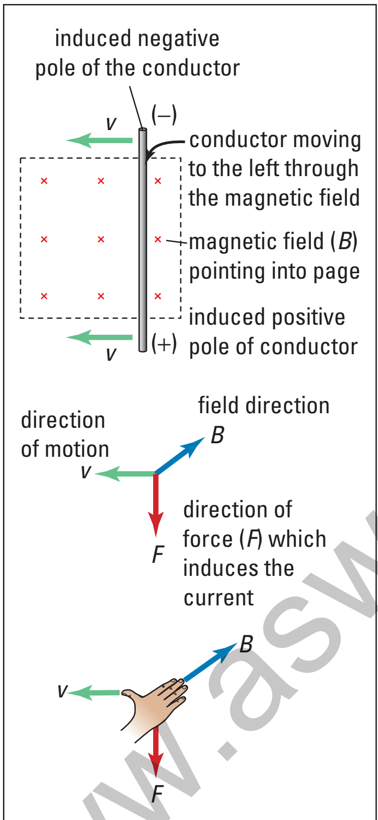


Figure 15.6 If an isolated conductor moves across a magnetic field, the generator effect induces the ends of the conductor to take on a polarity similar to a battery.

Electromotive Force

Until now, all discussion of electromagnetic induction has centred on the induced current. Since the motor effect was based on the presence of a current, it seemed natural to base the generator effect on currents as well. However, it turns out that it is more productive to discuss electromagnetic induction in terms of the electromotive force (*emf*) produced by the motion of the conductor in the circuit rather than the current.

If a rod is connected to a complete circuit, such as in Figure 15.4, then a current will be induced in the direction as shown. However, if the rod is not connected to an external circuit, the motor force on the charges within the rod still exist. The effect of the motor force is to push the charges in the rod toward the ends of the rod (Figure 15.6). Positive charges are pushed to the end of the rod in the direction of the motor force, while negative charges are pushed in the opposite direction. This action results in one end of the rod becoming positively charged and the other end becoming negatively charged. The ends of the rod, like the poles of a battery, now have a potential difference.

The action of the electromagnetic forces on the charges in a moving conductor parallels the electrochemical action inside a battery. In both cases, positive charges are moved onto the anode, leaving the cathode with a negative charge. In both cases, the potential difference between the anode and cathode can be used to move a current externally from the anode to the cathode.

In Chapter 13, you learned that if a battery is not connected to an external circuit, the potential difference is defined as the *emf*. When the battery supplied a current to a circuit, the terminal voltage was lower than the *emf* since some of the *emf* was used to move the current through the battery's internal resistance.

Like the *emf* of a battery, the induced *emf* (measured in volts) is independent of the internal resistance, since it is calculated when there is no current. Just like the motor force (see Section 14.4), the induced *emf* varies directly as the magnetic field strength ($\boldsymbol{B}$); the velocity of the conductor through the field ($\boldsymbol{v}$); and the length ($\boldsymbol{L}$) of the conductor in the magnetic field.

As expected, the product of the units for these three quantities produces the units for *emf* (volts).

$$emf = vB_{\perp}L$$

$$\left(\frac{\mathrm{m}}{\mathrm{s}}\right)(\mathrm{T})(\mathrm{m}) = \left(\frac{\mathrm{m}}{\mathrm{s}}\right)\left(\frac{\mathrm{N}}{\mathrm{A \cdot m}}\right)\mathrm{m}$$

$$= \frac{\mathrm{N \cdot m}}{\mathrm{A \cdot s}}$$

$$= \frac{\mathrm{J}}{\mathrm{C}}$$

$$= \mathrm{V}$$

Once the induced *emf* of a system has been found, then the induced current in a circuit of known resistance can be calculated using Ohm's law, in the same way as for a battery-driven circuit.

The polarity of the conductor moving through the field can be found if you use the right-hand rule for the generator effect. The thumb points in the direction of the motion of the conductor, the fingers point in the direction of the field, and the palm pushes charges toward the positive pole of the conductor.

AC Generators

Until now, only the linear motion of conductors through magnetic fields has been discussed. This type of motion does allow for sustained current production; however, the solution to that problem has already been presented. Just as the electric motor produces a continuous rotation of a coil that carries a current inside a magnetic field, the electric generator produces a continuous current from a coil that rotates in a magnetic field. In fact, the two devices are essentially the same design.

In Figure 15.7, a rectangular coil is rotating counter-clockwise in the magnetic field, which points from right to left. The right edge of the coil is moving upward through the magnetic field. By Lenz's law, the *emf* in the right edge of the coil has its positive end nearest the viewer. On the left edge of the coil, which is moving downward, the positive end of its edge is farthest from the viewer. The *emf*s for the edges of the coil are like cells in series. They add together to produce an *emf* for each loop of the coil that is twice

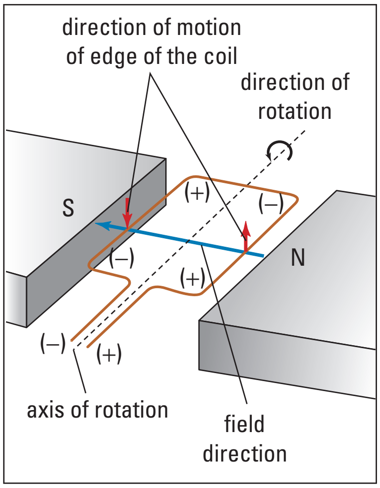
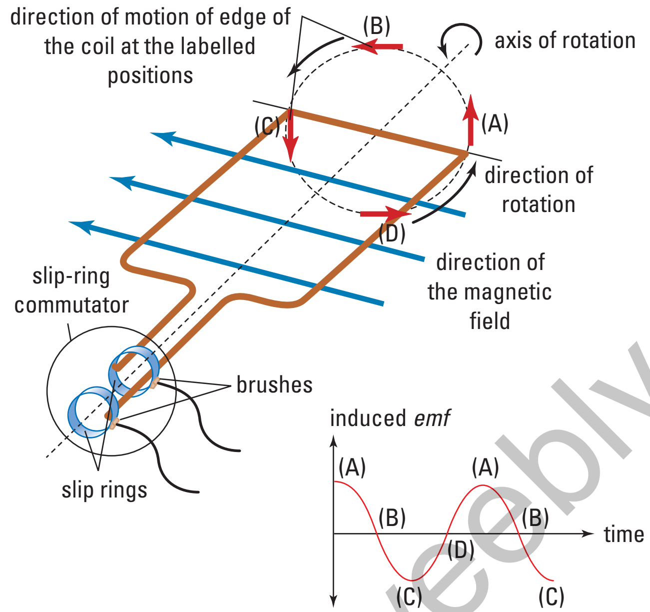


Figure 15.7 When a coil is rotated in a magnetic field, the edges of the coil cut the magnetic lines of force to induce an *emf* in the coil.

Figure 15.8 When the armature of a generator is rotated between the poles of the field magnets, an alternating *emf* is produced.



PHYSICS FILE

Since copper is diamagnetic, it is not attracted or repelled by magnets at room temperatures unless the magnets are very powerful. This property makes copper an ideal material for exploiting or investigating electromagnetism. For example, if steel rather than copper wire had been used to investigate the motor effect in Chapter 14, there would have been little to observe. Because steel is ferromagnetic, the steel wire would have been strongly attracted toward the poles of the magnet so that the force of the magnetic field on the current in the wire would have gone unnoticed. On the other hand, a conductor made of copper does not interact directly with the magnet; therefore, the only observable effect was the motor force. The same is true for the generator effect.

the *emf* of a single edge. Each turn of the coil adds two more edges in series, so that the total *emf* for the generator is the *emf* of each turn multiplied by the number of turns. This makes it possible to design generators that produce any desired *emf*.

An **AC generator** has an armature, which is a copper coil wound around an iron core. As in an electric motor, the magnetically permeable iron core inside the coil greatly enhances the strength of the field inside the coil. When the armature is rotated, the edges of the coil cut across the lines of force of the magnetic field to produce an induced current in the coil. Like the motor, the current in the coil is transferred to the fixed body of the generator by brushes sliding on a **slip-ring commutator** (Figure 15.8). This consists of two unbroken brass or copper rings.

Using a slip-ring commutator, rather than a split-ring commutator, means that the brushes are always in contact with the same end of the coil. When the right edge of the coil is moving upward through the field (position A in the diagram), the slip ring nearest the viewer is the positive end of the coil. However, on the other half of the rotation, when the same edge is moving downward (through position C), the slip ring farthest from the viewer is positive.

Even though the coil is rotating at a constant speed, the induced *emf* is not constant. The edges of the coil cut across the lines of force at the greatest speed when they are moving at right angles across the lines of force. This occurs when the edges of the coil are at positions A and C in the diagram. When the edges of the coil are passing through those positions, the induced *emf* in the coil is the greatest.

As the edges of the coil move through positions B and D in Figure 15.8, they are moving parallel to the lines of force. Since, at that instant, the edges are not cutting any lines of force, the induced *emf* is zero. At positions B and D, the edges of the coil are in the process of reversing their directions of motion through the field. The edge that was moving up on the right side is now starting to move down on the left side and vice versa. As the directions of the edges of the coil reverse, so does the direction of the induced *emf* in the coil, resulting in an AC generator. The actual speed at which the edges of the coil cut the lines of force varies as the sine of the angle between the direction of the lines of force, and the direction of the motion of the edge. Thus, AC generators produce the characteristic sine wave pattern of AC electricity.

DC Generators

As you saw in Section 14.4, in the DC motor, a split-ring commutator is used to convert the incoming DC current into an AC current in the motor coil. Similarly, in a **DC generator**, a split-ring commutator is used to replace the slip-ring commutator. As the coil rotates, the induced current reverses in the coil. At the same instant that the current changes direction in the coil, the brushes cross the gap from one half of the split ring to the other half, so that the current always leaves the generator in one direction. The current still increases and decreases depending on the angle at which the edges of the coil cut through the magnetic field. Thus, the sine wave output of the AC generator is converted into a pulsating DC output (Figure 15.9). This type of current is referred to as a **rectified** (made upright) **DC current**.

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and follow the **Physics 11** links for a laboratory activity on induced electric current.

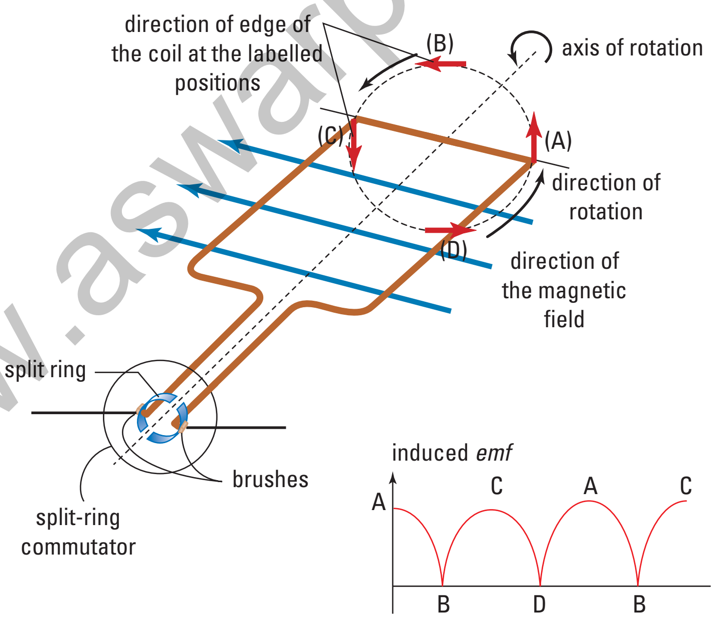


Figure 15.9 The split-ring commutator in a DC generator rectifies the output of an AC generator to produce a pulsating DC output.

Alternators

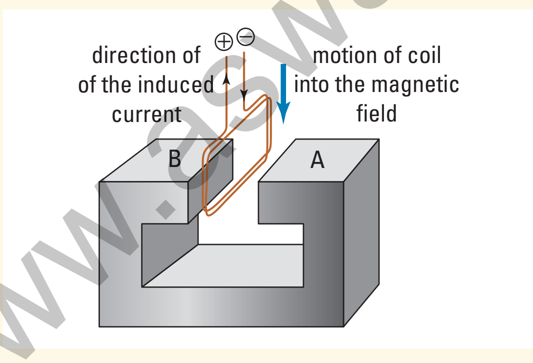
Every time the brush of a DC generator crosses over from one half of the split-ring commutator to the other, a tiny electric arc is formed. Eventually, this will cause the brushes to fail. Since the brushes on a slip-ring commutator slide continuously on the same ring, they last much longer than the brushes on a split-ring commutator. Today, the **alternator**, a device that uses diodes to rectify the output of an AC generator, is more common than DC generators.

15.1 Section Review

1. K/U A conductor is oriented horizontally parallel to the north-south direction. It is moving eastward through a magnetic field that points directly downward. In which direction does the induced current flow through the conductor?

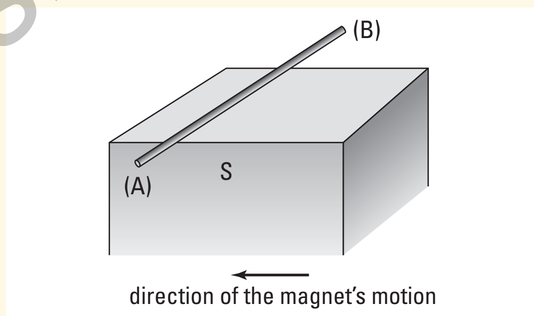
2. K/U A loop of wire lies in the horizontal plane. A bar magnet, with its S-pole pointing downward, is lowered into the loop from above. As seen from above, in which direction will the induced current move around the loop?

3. K/U A coil is dropped into the magnetic field between the poles of a horseshoe magnet. If the current in the coil is in the direction indicated, which pole of the magnet (A or B) is its N-pole?



4. K/U A coil of wire lies in the same plane as the page. The pole of a bar magnet is moved toward the coil along the axis of the coil. The induced current resulting from the motion of the magnetic field is clockwise around the coil. Which pole of the magnet approached the coil?

5. K/U The S-pole of a magnet points vertically upward below a conductor. If the magnet is moved from right to left, which pole of the conductor (A or B) will become positively charged?



UNIT PROJECT PREP

Generators convert mechanical energy into electrical energy and motors convert electrical energy into mechanical energy.

- How can you use the results of Investigation 15-B to improve your motor design? For example, what is the effect of using a coil with a different number of windings?
- What other design ideas can you get from small, battery-operated toys?

15.2 Lenz's Law

To find the direction of the induced current using the right-hand rule and the motor effect, as in Figure 15.4 (page 723), is sometimes quite difficult. This is especially true when there is no apparent motion of the coil relative to the lines of force. An obvious example of this occurs in Faraday's original experiment with the coils wrapped around the iron ring. In 1834, a Russian physicist, Heinrich Lenz (1804–1865), devised an alternate method of finding the direction of the induced current.

SECTION EXPECTATIONS

- Define and describe Lenz's law.
- Identify the direction of induced electric current resulting from a changing magnetic field.
- Explain the relationship between induced current and the conservation of energy.

KEY TERMS

- Lenz's law
- back *emf*
- magnetic damping
- eddy currents

Induced Current and the Conservation of Energy

Lenz realised that when Faraday moved the bar magnet through the coil (Figure 15.3, page 719), he was generating electrical energy in the form of the induced current. By the law of conservation of energy, the gain in electrical energy had to come from the kinetic energy of the magnet moving through the coil. The transfer of energy from one object to another is, by definition, work. Work, in turn, requires a force. To remove kinetic energy from the magnet requires a force that acts in the opposite direction to the motion of the magnet. If the magnet could move unimpeded through the coil, then no work would be required to create the electrical energy. Lenz argued that, by the law of conservation of energy, whenever a conductor interacts with a magnetic field, there must be an induced current that opposes the interaction. This conclusion is known as **Lenz's law**.

LENZ'S LAW

When a conductor interacts with a magnetic field, there must be an induced current that opposes the interaction, because of the law of conservation of energy.

The pickup of an electric guitar, shown in Figure 15.10, is made of a permanent magnet surrounded by a tiny coil of wire. When the ferromagnetic metal string of an electric guitar is plucked, its motion near the magnetic field of the pickup causes the strength of the magnetic field inside the coil to fluctuate. By Lenz's law, a very weak current, whose magnetic field opposes the variations in magnetic field strength produced by the vibrating string, is induced in the coil. The current is then amplified and sent to a loudspeaker that converts the current back into sound.

Figure 15.10 Electric guitar pickups rely on Lenz's law.

INVESTIGATION 15-C

Lenz's Pendulum

TARGET SKILLS

- Hypothesizing
- Analyzing and interpreting

In this investigation, a pendulum, in the form of a copper coil, is set to swing back and forth through a magnetic field. Because copper is diamagnetic, any effect the magnet has on the motion of the pendulum must be due to factors other than the interaction of the copper and the magnet.

Problem

Observe the effect of a magnetic field on the motion of a conductor through the field, and formulate a hypothesis to account for your observations.

Predictions

In each part of the investigation, make a prediction about the motion of the pendulum.

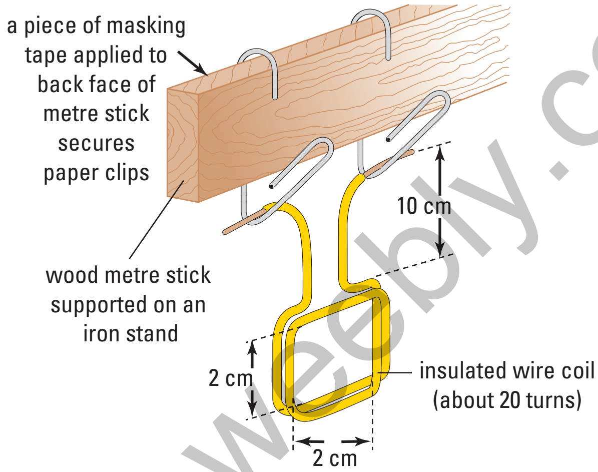
Equipment

- bar magnets (2)
- copper coil (20 turns, 2 cm × 2m)
- galvanometer
- retort stand
- masking tape
- metre stick
- 2 large paper clips
- wax blocks
- elastic bands
- alligator clip leads

Procedure

Part 1

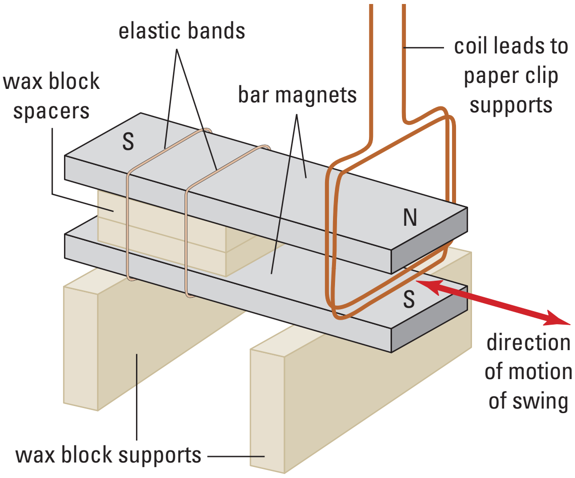
1. Prepare the coil by wrapping 20 turns of copper wire around a square block to form a square coil approximately 2 cm by 2 cm. Leave 15 cm of wire on each end of the coil.
2. Use masking tape to secure the metre stick at the edge of the retort stand.
3. Suspend the coil from the metre stick using paper clips taped onto the stick as shown in the diagram. Remove enough insulation from the ends of the coil leads so that bare copper wire is in contact with the paper clips.



4. Set the pendulum in motion. Adjust the positions of the paper clips so that the pendulum swings smoothly beneath the metre stick. Use a piece of masking tape to secure the clips on the metre stick. (**Note:** Do not place the magnets near the coil until Part 2.)
5. Move the bottom of the coil sideways about 1 cm from its vertical rest position. Allow the coil to swing back and forth until it comes to rest. Record the number of oscillations (swings) required for it to come to rest.
6. Move the coil sideways about 2 cm and release it. Count and record the number of swings required for the coil to come to rest.

Part 2

7. Mount the bar magnets on the wax blocks. Position the magnets so that the lines of force of the magnetic field from the bar magnet cut perpendicularly across the lower edge of the coil. Make sure that the coil will swing without touching the magnets.

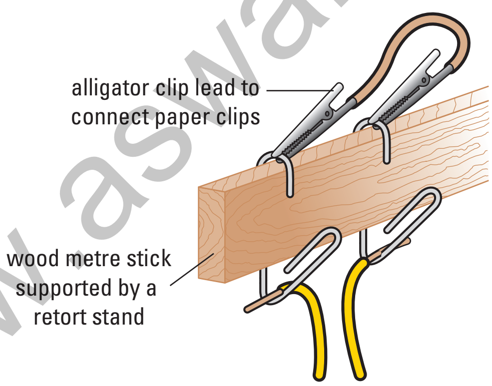


8. With the magnets in place, pull the coil sideways 1 cm and release it. Count and record the number of oscillations required for the coil to come to rest.

9. Pull the coil 2 cm to the side and release it. Count and record the number of oscillations required for the coil to come to rest.

Part 3

10. Use an alligator clip lead to connect the paper clips supporting the coil.



11. Pull the coil 1 cm to the side and release it. Count and record the number of swings required for the coil to come to rest.

12. Pull the coil 2 cm to the side and release it. Count and record the number of swings required for the coil to come to rest.

Analyze and Conclude

1. Did the presence of the magnets in Part 2 affect the swing of the coil? If so, describe the difference. Was a different number of swings required for the pendulum to come to rest? Was there any noticeable qualitative difference in the swing of the pendulum? Why do you think that the pendulum behaved as it did?

2. In Part 3, when a wire was used to connect the paper clips that support the pendulum, did the motion of the pendulum change? If so, describe the difference.

3. What might have happened in the coil when the wire connected with the paper clips, that could not have happened in Parts 1 and 2?

4. Formulate a hypothesis that could account for your observations. Record your hypothesis in your logbook. Later, when you have completed the chapter, come back and review your hypothesis.

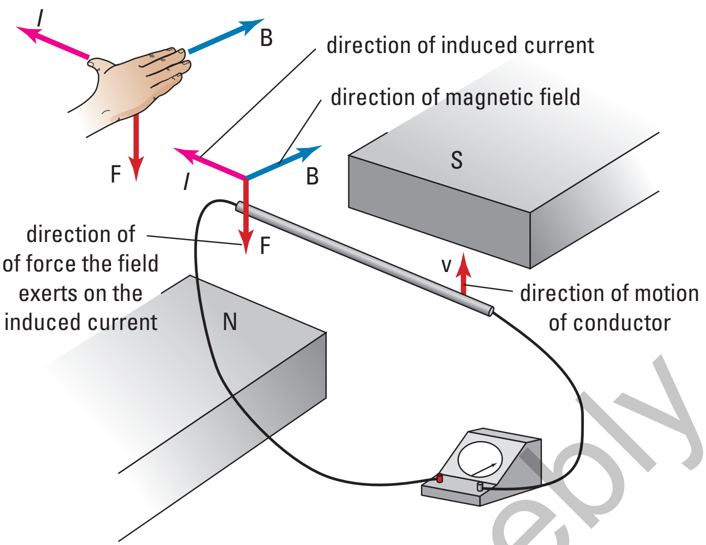
Apply and Extend

5. Connect the paper clips supporting the coil to a galvanometer and set the coil in motion between the magnets.

6. Record the reaction of the galvanometer to the motion of the coil in the magnetic field.

7. Move the magnets away from the coil and set the coil in motion again. Is there any change in the motion of the coil? Does the motion of the coil seem to be related to the reaction of the galvanometer? Explain.

Figure 15.11 The direction of the force exerted by the magnetic field on an induced current is opposite to the motion of the conductor through the magnetic field.



Re-examine the system in Figure 15.4 in light of Lenz's law. Firstly, recall that for the generator effect, the right-hand rule was applied in the following manner: the thumb indicated the motion of the conductor through the field; the fingers were pointed in the direction of the lines of force; and the palm pushed in the direction of the force on the positive charges in the conductor, and thus in the direction of the induced current. In Figure 15.4, this indicated that the induced current would move from right to left.

In contrast, Lenz's law states that the direction of the force the magnetic field exerts on the induced current must oppose the direction of the motion of the conductor. To apply the right-hand rule with Lenz's law, point your fingers in the direction of the lines of force and orient your palm to exert a force that opposes the motion of the conductor through the field (Figure 15.11). The thumb then must be pointing in the direction of the induced current.

In the previous case, there does not seem to be much advantage to using Lenz's law over the generator effect. But look back at how the generator effect was used in Figure 15.5 (page 724). In this case, a variation of right-hand rule #2 can be used to simplify finding the direction of the induced current in a coil or solenoid.

According to Lenz, as the bar magnet is moved upward toward the centre of the coil, the motion of the magnetic field must induce a current in the coil that interacts with the field to oppose the motion of the magnet. Since the N-pole of the magnet is approaching the coil, the induced current creates a magnetic field inside the coil with lines of force that point downward, pushing the N-pole of the magnet away from the coil.

The direction of the magnetic field for a coil is found using right-hand rule #2. Place your fingers along the edge of the coil in the direction of the current, and your thumb will point in the direction of the lines of force inside the coil. In this case, you want the magnetic field to point downward so that the N-pole of the magnet experiences a force downward. Place the fingers of your right hand along the edge of the coil so that your thumb points downward (the direction of the magnetic field through the coil). Your fingers lie along the edge of the coil in the direction of the induced current (Figure 15.12(A)).

When the N-pole of the magnet, positioned below the coil, is moved away from the coil, Lenz's law states that the magnetic field from the induced current still opposes the motion. To stop the N-pole moving away from the coil, it must try to pull the N-pole of the magnet toward the coil. The N-pole of a magnet experiences a force in the direction of the field acting on it, thus the magnetic field inside the coil would have to be directed upward. Placing your fingers along the edge of the coil, so that the thumb is pointing upward, gives the direction of the induced current in the loop (Figure 15.12(B)).

If the coil in Figure 15.12 had not been connected to the galvanometer, then the ends of the coil would have gained positive and negative charges like the anode and cathode of a battery. The end of the coil to which the current flowed would have become the anode.

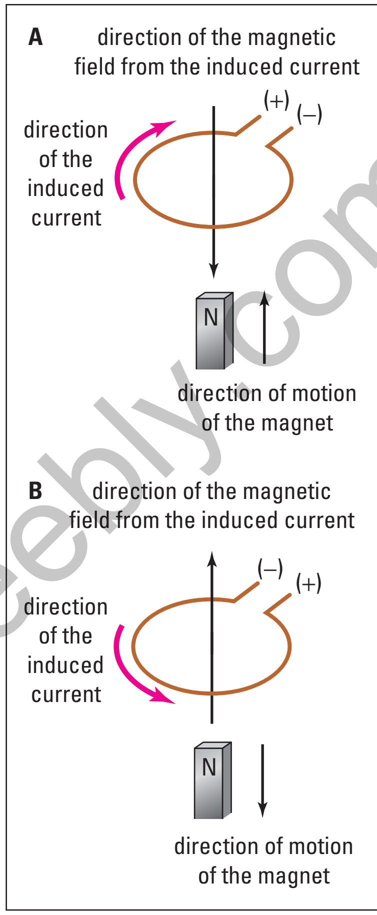


Figure 15.12 When a conductor and a magnet move in relation to each other, by Lenz's law, the induced current creates a magnetic field that opposes the motion.

Back *emf*

When an electric motor is switched on, the magnetic field around the armature exerts a force on the current in the coils. This force causes the armature to rotate within the magnetic field. As long as a current flows through the coils, the magnetic field exerts a force on the armature. However, if forces cause accelerations, why does the armature of the motor not continue to accelerate to an increasingly faster rate of rotation? It should not be too surprising to find that the answer is found in Lenz's law.

As the armature speeds up, its coil is moving through the magnetic field that drives the motor. However, the generator effect states that the motion of the coil in the field must result in an induced *emf*. Lenz's law says that the direction of the induced *emf* (and induced current) must oppose the *emf* (and the current) supplied by the battery.

Once again, consider the simple case of a single conductor inside a magnetic field. The conductor is connected to a battery (Figure 15.13, page 734). The battery causes a current in the conductor from left to right. The right-hand rule for the motor force indicates that the direction of the force on the conductor is toward the top of the page. If this conductor is free to move, it will move in that direction.

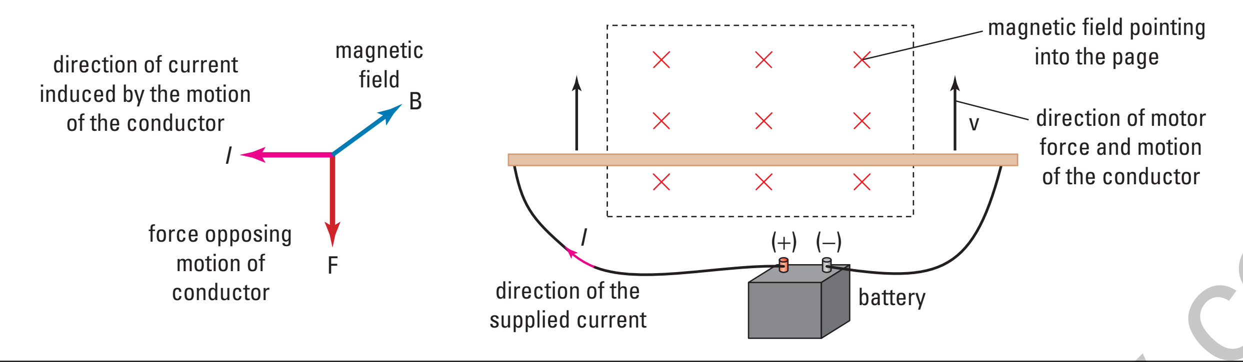


Figure 15.13 As the current from the battery experiences the motor effect, the motion of the conductor in the field induces a back *emf* that opposes the supplied *emf*.

As soon as the conductor begins to move upward, the generator effect begins. By Lenz's law, the motion of the conductor, toward the top of the page through a magnetic field into the page, results in an *emf* across the conductor that pushes a current from right to left, opposing the current from the battery. This is defined as the **back *emf***. As the conductor speeds up, the back *emf* increases. In the absence of friction, the speed of the conductor would increase until the back *emf* equalled the supplied *emf* from the battery. At that point, the net *emf* (and thus the net current through the conductor) would be zero, and the conductor would be moving in equilibrium at a constant speed.

When a motor begins to run, the rate at which the armature rotates continues to increase until equilibrium is reached. Since there is always friction, the top speed of the armature is such that the back *emf* is a bit smaller than the *emf* of the battery. This leaves a net *emf* that causes just enough current through the armature so that the forward force of the motor effect equals the drag of the force of friction. The armature is now in dynamic equilibrium, and moves at a constant speed.

If the load on a motor is increased, then the rate of rotation of the armature slows down. As it slows down, the back *emf* is reduced and the net *emf*, in the forward direction, increases. The armature continues to slow down until the net current through the coils increases enough so that motor force on the resulting current is sufficient to drive the increased load.

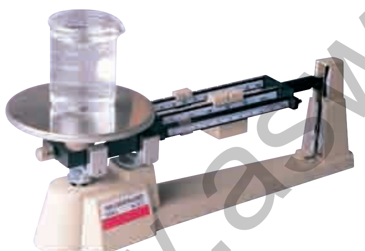


Figure 15.14 The motion of the arm in the triple-beam balance results in eddy currents in the plate at the end of the arm. By Lenz's law, the energy to cause the eddy currents must come from the kinetic energy of the arm, damping its motion.

Eddy Currents and Magnetic Damping

Magnetic damping is a common application of Lenz's law. Sensitive balances, such as the equal triple-beam balances or electronic balances used in laboratories, would require considerably more time to come to rest if they were not magnetically damped (slowed down). A flat plate of diamagnetic or paramagnetic material (copper or aluminum) is attached to the arm of the scale so that it is inside a magnetic field (Figure 15.14). As the arm of the scale moves up and down, the magnetic field induces **eddy currents** (small circular currents) within the plate.

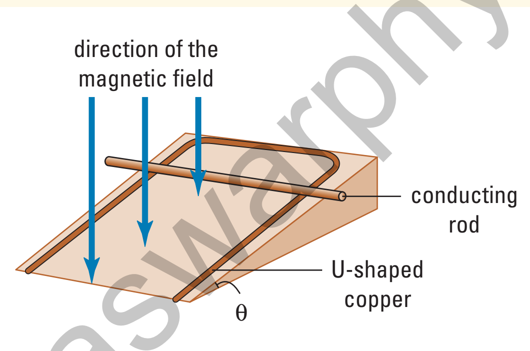
By Lenz's law, the direction of the eddy currents is such that the motor force on them opposes the motion of the plate, slowing down the motion of the arm. As the motion of the arm slows down, the damping effect of the eddy currents is reduced so that the final position, and thus the accuracy of the scale, is not affected.

Go back to Investigation 15-B. Can you explain your observations in terms of Lenz's law and the law of conservation of energy?

15.2 Section Review

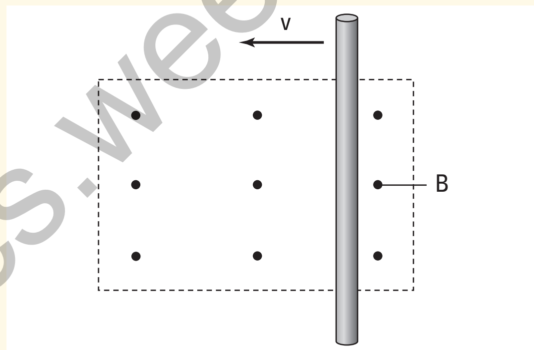
1. **C** Return to the five questions at the end of section 15.1 and use Lenz's law to find the answers. Compare how you applied Lenz's law and the right-hand rule interpretation of the generator effect. For each question, compare how the right-hand rule applies using the generator effect, and how it applies using Lenz's law.

2. **K/U** A ramp is made using a U-shaped copper rod that slopes to the left. The magnetic field around the ramp points vertically downward. If a copper rod is allowed to roll down the ramp, in which direction is the induced current in the rod?



3. **K/U** A coil lies in the plane of the page. When a bar magnet moves toward the coil, along the axis of the coil from behind the page, a current is induced in the coil in a counter-clockwise direction. Which pole of the magnet is approaching the coil?

4. **C** The diagram (upper right) shows a rod moving through a magnetic field pointing out of the page. Explain how to use the right-hand rule with Lenz's law to decide which end of the rod will become positively charged.



5. **C** Draw a diagram of a plate, lying in the plane of the page, and moving towards the bottom of the page, so that it will pass through a magnetic field that points directly out of the page. Apply Lenz's law to determine the direction of the eddy current that will act to damp the motion of the plate. Hint: It may help to analyze the induced currents in the plate when the eddy is just entering and leaving the field.

UNIT PROJECT PREP

- Lenz's law predicts the effect of the back *emf* on an electric motor.
- What is the effect of the back *emf* on the motion of an electric motor?
- To what extent should you be aware of eddy currents and magnetic damping within your motor design?

15.3 Transformers

SECTION EXPECTATIONS

- Explain the interaction of electricity and magnetism in the operation of transformers.
- Compare direct current and alternating current in qualitative terms as they relate to the transmission of electric energy.
- Analyze the operation of industrial applications of transformers.

KEY TERMS

- primary coil
- secondary coil
- step-up transformer
- step-down transformer
- transformer formula

Figure 15.15 Electromagnetic induction in transformers delivers power efficiently and safely to your home.

A basic component of the electric power system, transformers like the one in Figure 15.15 convert power from the high voltages used in transmission to low voltages that are safe for use in your home.

Power Transmission over Long Distances

When you do electricity experiments in the laboratory, the distances between the power supply and the load are small, so you can ignore the internal resistance of the leads used to connect the components of the circuits. However, when power companies transmit electricity over hundreds of kilometres between the generating station and the user, the internal resistance of the transmission lines becomes significant.

In all circuits, the connections between the supply and the load always have resistance, and thus always convert some of the energy of the supply to heat. In the long-distance transmissions from the generating station to your home, this becomes a major problem.

During transmission, the rate at which electrical energy is converted to heat is calculated by the equation

$$P = I^2R$$

where I is the current being transmitted, and R is the resistance of the transmission line. Therefore, there are only two ways to reduce this power loss. First, use conductors with the lowest possible resistance per unit of length. (For this reason, power lines are as thick as possible, and made out of materials with low resistance.) Second, reduce the amount of current. (The large distances over which transmission occurs means that the resistance of the lines is still considerable.)

If the current is reduced, why isn't the rate at which power is being transmitted also reduced? At first, it seems to be a losing battle, but there are ways to reduce the current and still maintain a high rate of power transmission. Remember that electric power can also be calculated using $P = IV$. This means that a high voltage and low current can transfer the same power as a low voltage and high current.

For example, assume that you wanted to transmit power at the rate of 1.00×10^6 W over a transmission line, with an internal resistance of only 10.0 Ω. Using a voltage of 1.00×10^4 V, the power loss to heat works out to be 1.00×10^5 W. This represents a huge fraction, in fact ten percent, of the rate of transmission.

On the other hand, transmitting at 1.00×10^5 V, loss to heat would be just 1.00×10^3 W. While 1000 W may seem quite a large loss, it represents only one tenth of one percent of the transmitted power.

This argument highlights the need for a method by which voltages could be stepped up and stepped down as required. In fact, probably the strongest argument for choosing Tesla's AC electrical system over Edison's DC system, is the ease and efficiency with which transformers can change the potential difference and current of AC electricity.

Between the generator at the power station and the light bulb in your home, the potential difference of the electric supply has been stepped up (increased in voltage) and stepped down (decreased in voltage) several times. During transmission across the country, voltages in the range of 500 000 V are common, but in your home they would be lethal. The line voltage that services your home is 120 V. You now have the framework of theory to explain how transformers accomplish these voltage changes.

Fluctuating Magnetic Fields

In the previous sections of this chapter, the relative motion of a conductor through a field was used to create the induced current. However, if you look back, the first instance of an induced current was produced without any apparent relative motion of a conductor and a field.

Faraday originally discovered the generator effect using solenoids wrapped around the edges of an iron ring. The induced current was produced only when the switch to the **primary coil** (the coil connected to the supply) was opened or closed. But Faraday was quite right when he hypothesized that the cause of the induced current was the growth and collapse of the magnetic field.

Math Link

In the example given, the transmission power is 1.00×10^6 W and the resistance is 10.0 Ω. For a voltage of 1.00×10^5 V, calculate (a) the current in the transmission and (b) the power lost to heat, stating which formula you are using. Repeat your calculations for a voltage of 1.00×10^4 V.

Web Link

www.school.mcgrawhill.ca/resources/

Nikola Tesla and Thomas Edison were close contemporaries, perhaps the two greatest inventor-engineers of their time. They even worked together for a few years. Edison today is by far the more famous, yet Tesla's power transmission system and AC motor seem likely to last well into the new century, while Edison's best-known inventions, the incandescent light bulb and analogue recording, are steadily being replaced by newer technologies. For more information on Tesla's inventions and his roller-coaster career, go to the above address. Follow the **Science Resources** and **Physics 11** links to find out where to go next.

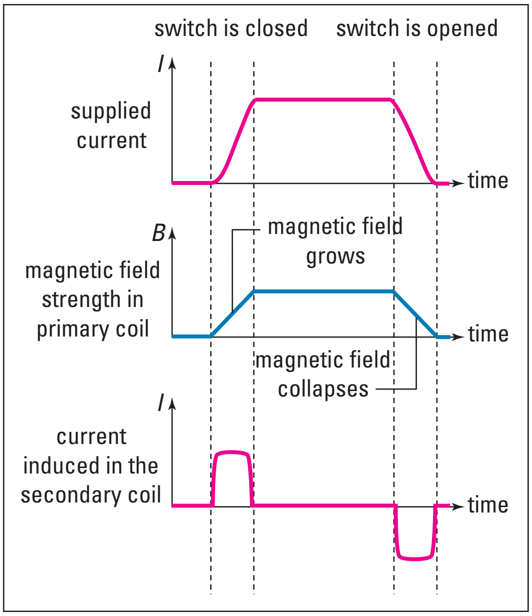


Figure 15.16 When a current begins or stops, the increase or decrease in current causes the magnetic field to fluctuate in strength. When the magnetic field grows, it induces a current in one direction; when it collapses, it induces a current in the opposite direction.

Faraday demonstrated that a change in the strength of the magnetic field is responsible for the induced current, as Figure 15.16 shows. Since opening and closing a switch to change the magnetic field strength is rather clumsy, a simpler way would be to change the strength of the current in the primary coil. As the current in the primary coil changes, the strength of the magnetic field in the iron ring fluctuates, and induces a current in the **secondary coil**, which is *not* directly connected to the supply. It turns out that AC current is the ideal system to do exactly that.

As an AC current alternates, it continuously increases and decreases and, in turn, causes the strength of the magnetic field produced by the primary coil to increase and decrease. The fluctuating magnetic field in the iron ring induces a current in the secondary coil that, by Lenz's law, creates a magnetic field that opposes the *changes* in the magnetic field from the primary coil.

It is important to note that the induced current in the secondary coil is not as a result of the *strength* of the magnetic field in the primary coil, but rather, as a result of the *changes* in the strength of the magnetic field. Therefore, as the magnetic field grows, it induces a current that produces a magnetic field in opposition to the growth of the magnetic field from the primary coil (Figure 15.17). Since the field is trying to increase its strength in the upward direction through the secondary coil, the magnetic field from the induced current in the secondary coil must point downward to oppose the growth.

As the current in the primary coil reduces, the magnetic field from the primary coil collapses. This collapse results in a reduction in the strength of the field in the upward direction. In essence, the direction of the field is increasing in a downward direction. The current it induces in the secondary coil produces a magnetic field that tries to sustain the strength of the weakening magnetic field from the primary coil (Figure 15.18). In order to try to stop the field from becoming weaker, the magnetic field from the induced current must also be upward.

The AC current in the primary coil, and the magnetic field generated by it, are constantly changing both strength and direction. Thus, in reaction to changes in the magnetic field, the induced current in the secondary coil is constantly changing strength and direction. Thus the secondary current is also alternating. Critically, the relative values of the voltage supplying the primary coil, and the induced voltage at the secondary coil, depend on the relative numbers of turns in their coils.

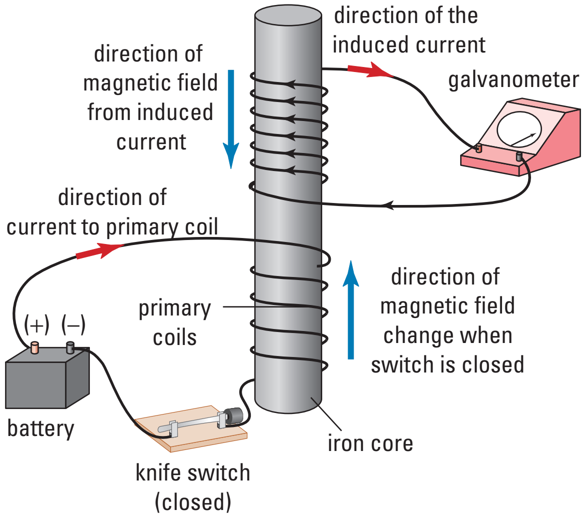


Figure 15.17 When the current is increasing in the primary coil, Lenz's law dictates that the direction of the magnetic field, from the current induced in the secondary coil, must oppose the growth of the field.

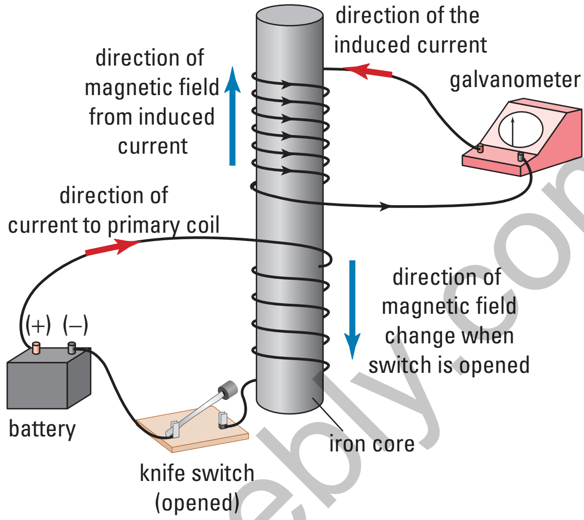


Figure 15.18 As the current and its induced magnetic field in the primary coil diminish, the induced current in the secondary coil tries to sustain the field strength. The direction of the induced current creates a magnetic field in the same direction as the field from the primary coil.

Step-up and Step-down Transformers

In a generator, the size of the induced *emf* depends on the strength of the magnetic field, the speed of the generator, and the length of wire in the field. In a transformer, the first two factors, field strength and rate at which the field changes, are the same for both the primary and secondary coils. However, there is no reason why the secondary coil should have the same number of turns of wire as the primary coil. If the secondary coil has ten times as many turns of wire around the core as the primary coil, then the length of wire it has in the magnetic field would be ten times as great as the primary coil.

The result is that the induced *emf* in the secondary coil would be ten times the supplied *emf* to the primary coil. This type of transformer is called a **step-up transformer** since the secondary (induced) *emf* is greater than the primary (supplied) *emf* (Figure 15.19).

A **step-down transformer** has fewer turns of wire in the secondary coil than in the primary coil. The result is that the secondary *emf* is less than the primary *emf*.

In both step-up and step-down transformers, the ratio of the secondary *emf* (V_S) to the primary *emf* (V_P) is the same as the ratio of the number of turns in the secondary coil (N_S) to the number of turns in the primary coil (N_P). Hence

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

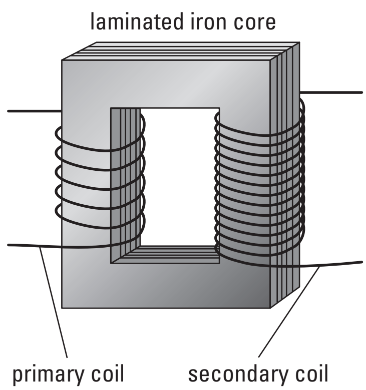


Figure 15.19 A step-up transformer is created when the number of turns of wire in the secondary coil is greater than the number of turns in the primary coil. The induced voltage produced at the secondary coil is greater than the supplied voltage input at the primary coil.

PROBEWARE

If your school has probeware equipment, visit the **Science Resources** section of the following web site: ***www.school.mcgrawhill.ca/resources/*** and follow the **Physics 11** links for a laboratory activity on transformers.

At first it might seem that if voltage output from the secondary coil is greater than voltage input to the primary coil, then it should also produce a greater current. If that were true, the output energy of the transformer would be greater than the input energy. The law of conservation of energy says that is not possible. If transformers were 100% efficient, then the power out at the secondary coil (P_S) would exactly equal the power in at the primary coil (P_P). Assuming 100% efficiency,

$$P_S = P_P$$

Since $P = IV$, then

$$I_S V_S = I_P V_P$$

$$\therefore \frac{I_S}{I_P} = \frac{V_P}{V_S}$$

Note that the ratio of currents and the ratio of turns in the secondary and primary coils are both equal to the ratio of the *emf*'s. Therefore, the ratios are equal to each other. The resultant equality is known as the **transformer formula**.

TRANSFORMER FORMULA

The ratio of primary and secondary voltages in a transformer is equal to the ratio of turns in the primary and secondary coils, and equal to the ratio of *secondary* and *primary* currents.

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

Quantity	**Symbol**	**SI unit**
primary voltage	V_P	volts (V)
secondary voltage	V_S	volts (V)
primary coil turns	N_P	no unit
secondary coil turns	N_S	no unit
primary current	I_S	amps (A)
secondary current	I_P	amps (A)

Unit Analysis

The units cancel in each ratio.

Note: The current ratio part of the formula only applies if the efficiency is 100%.

MODEL PROBLEM

Transforming Electricity

The primary coils of a transformer contain 150 turns, while the secondary coil contains 1800 turns. What will be the voltage and current outputs of the transformer if the input to the primary coil is 3.60 kW of power at 250 V? Assume the efficiency is 100%.

Frame the Problem

- The *secondary voltage* can be found using the *primary voltage* and the *transformer formula*.
- The *secondary current* can be found in two ways. First, use the *secondary power* and the *secondary voltage* to find the secondary current. Second, use the *primary power* and the *primary voltage* to find the *primary current*. Use the *primary current* and the *transformer formula* to find the *secondary current*.

PROBLEM TIPS

- Make sure you have correctly identified primary coil quantities and secondary coil quantities.
- In unit analysis, remember that the numbers of turns are pure numbers with no units.
- Before you substitute numbers into it, convert the law from its given form into the form required to solve for the desired variable.
- The number of turns, *N*, is an exact number and does not affect the number of significant figures.

Identify the Goal

Find the secondary voltage, V_S, and the secondary current, I_S.

Variables and Constants

Involved in the problem		Known	Unknown
P_P	N_P	$P_P = 3.60$ kW	V_S
P_S	N_S	$V_P = 250$ V	P_S
V_P	I_P	$N_P = 150$	I_P
V_S	I_S	$N_S = 1800$	I_S

Strategy / Calculations

Solve for the secondary voltage. State equation with voltages and numbers of turns.

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Isolate the variable for secondary voltage.

$$V_S = \frac{V_P N_S}{N_P}$$

Substitute values for variables and solve.

$$V_S = \frac{(250\ \text{V})(1800)}{150}$$

The secondary voltage is 3000 V.

$$V_S = 3.00 \times 10^3\ \text{V}$$

Solve for the secondary current using secondary power. Since the system is 100% efficient the power input equals the power output.

$$P_S = P_P$$
$$P_S = 3.60 \times 10^3\ \text{kW}$$

Use the equation relating power, voltage and current to find the secondary current.

$$P_S = I_S V_S$$

$$\therefore I_S = \frac{P_S}{V_S}$$

$$I_S = \frac{3.60 \times 10^3\ \text{W}}{3.00 \times 10^3\ \text{V}}$$

The secondary current is 1.20 A.

$$I_S = 1.20\ \text{A}$$

The output of the secondary coil is 3.60 kW at 3000 V and 1.20 A.

continued ►

continued from previous page

Validate

Use the alternate method to find the secondary current. The primary current I_P is given by

$$I_P = \frac{P_P}{V_P} = \frac{3600 \text{ V}}{250 \text{ V}} = 14.4 \text{ A}$$

The secondary current I_S can be calculated directly from the primary current:

$$I_S = \frac{N_P}{N_S} I_P = \frac{150}{1800} \times 14.4 \text{ A} = 1.20 \text{ A}$$

as before.

PRACTICE PROBLEMS

1. A step-up transformer increases the voltage by a factor of 25. If there are 3000 turns in the secondary coil, how many turns does the primary coil contain?
2. The transformer near your house steps the voltage down to 2.40×10^2 V. If the primary coil of the transformer has 5000 turns, and the secondary coil has 750 turns, what was the line voltage leading into the transformer?
3. The generator at a hydroelectric facility produces a voltage of 7.50×10^2 V. This is stepped up to 6.00×10^5 V for transmission to the nearest town. At the town, it is stepped down to 1.5×10^4 V at an electrical substation, and then stepped down again to 2.40×10^2 V in your neighbourhood. If the total current available from the transformer in your neighbourhood is 6.0×10^3 A, find the current that must be transmitted at each step of the journey. Assume 100% efficiency.
4. A power station has an output of 5.00×10^3 MW. This is transmitted equally over 20 lines from the generating station to the electric substation where it undergoes the first step-down in preparation for delivery into your home. The transformers at the substation have 6000 turns in their primary coils, and 400 turns in their secondary coils. Each line from the generating station supplies electricity to one transformer. The primary voltage to the transformer is 4.50×10^5 V. What is the current output of the transformer? Assume 100% efficiency.

15.3 Section Review

1. **C** Explain why an AC current produces a continuous current in a transformer while a DC current does not.
2. **K/U** The primary coils of two transformers, P and Q, are identical. The secondary coils have the same number of turns. However, transformer P's secondary coil uses thinner wire and hence has a greater resistance than that in Q. How will the difference in resistance affect the outputs (power, voltage, and current) of the two transformers?
3. **I** Figure 15.16 on page 738 shows the relationship between primary current, induced magnetic field, and secondary current in Faraday's iron ring experiment, which used a simple DC current and a switch. Now suppose that the primary current is AC. Sketch a similar set of graphs for this situation. Use Lenz's Law, and be careful to show where the peaks and troughs in the secondary current occur.

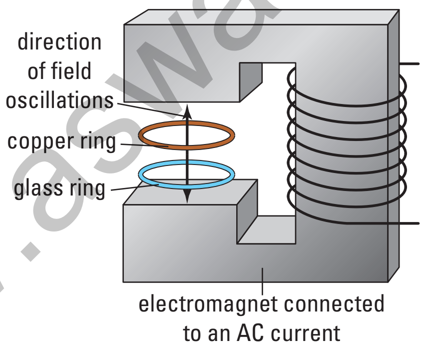
CHAPTER 15 Review

REFLECTING ON CHAPTER 15

- The direction of the current induced by the motion of a conductor through a magnetic field can be found using the right-hand rule.
- The *emf* induced by the motion of a conductor through a magnetic field varies directly as the speed v of the conductor, the field strength B, and the length L of the conductor in the field.
- When a coil rotates inside a magnetic field an alternating current is induced in the coil. A slip-ring commutator takes this current off as an AC current and a split-ring commutator takes the current off as a rectified DC current.
- Lenz's law is based on the law of conservation of energy. It states that the induced current, produced when any part of an electric circuit or magnetic field around the circuit changes, must be in a direction that opposes the change.
- Lenz's law states that a motor must generate a back *emf* that opposes the applied *emf*.
- Eddy currents circulate within the body of a conducting material when it moves inside a magnetic field or if the surrounding magnetic field varies in intensity. They are often used to dampen the motion of the conductor or to dissipate energy by heating.
- Transmission of electricity over long distances uses very low currents to reduce the energy lost to heat due to the resistance of the lines.
- Transformers can be used to step up or step down the potential difference of electrical energy. By the law of conservation of energy, when a transformer increases the voltage the current must undergo a corresponding decrease.

Knowledge and Understanding

1. Two circles, one of copper and one of glass, are placed in a fluctuating magnetic field so that the field passes through them parallel to their axes. Both glass and copper are diamagnetic materials. Compare the induced *emf* and current in each material.



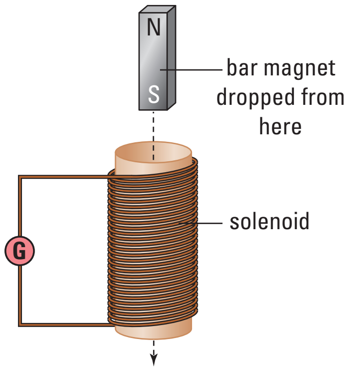
2. In a generator, what is the orientation of the coil with respect to the magnetic field when the generator output is at its peak?
3. What is the purpose of the commutator in a DC generator?
4. What is the source of energy for the alternator in your car?
5. The humidifier motor on a furnace requires a 24 V supply and a current of 3.0 A. These elements are provided by a transformer connected to a 120 V supply. Assuming 100% efficiency, calculate the current in the primary coil.

Inquiry

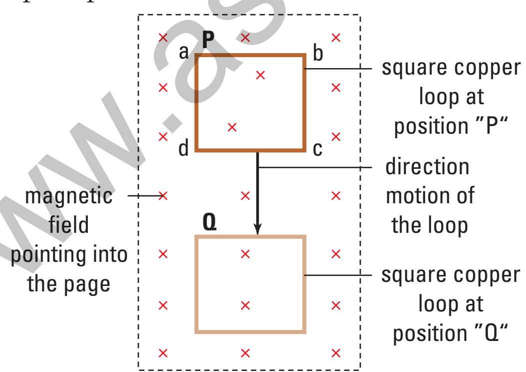
6. In Investigation 15-C page 730, the swinging of the coil is damped only when a lead connects the supports of the coil. Explain why this is the case.
7. In an automobile, every time you come to a stop the brakes convert the car's kinetic energy into heat. The energy saved would be enormous if the work done to stop the motion of a car could somehow be recycled. In fact, electric trains can do just that. Investigate how the kinetic energy is transformed and recycled.
8. When a coil is connected to an AC power source, a phenomenon called self-inductance occurs. Investigate this phenomenon and how it affects the function of the coil.

Communication

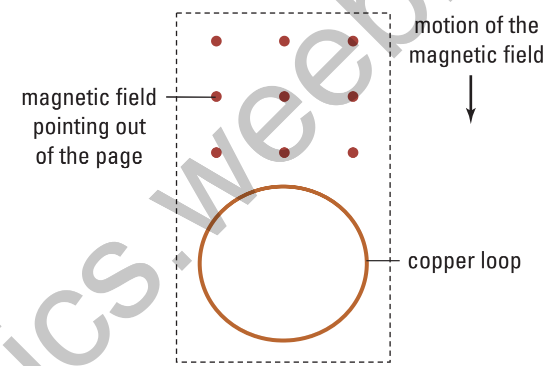
9. A bar magnet is dropped, S-pole first, into a solenoid connected to a galvanometer. Discuss the nature of the induced current in the solenoid as the magnet passes through and out the other end. As a frame of reference, use the view looking down into the solenoid.



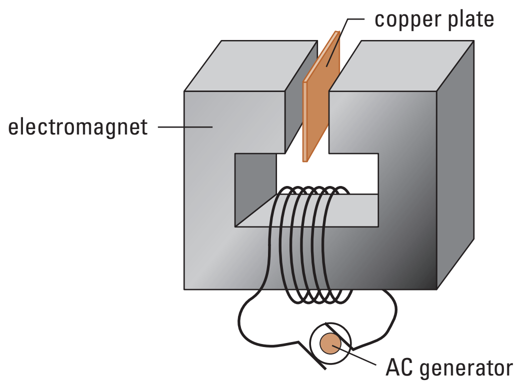
10. At the same instant as the bar magnet in Question 9 is dropped, a second bar magnet is dropped from the same height above the floor. The second magnet falls parallel to the first magnet, but does not pass through the solenoid. Explain why the second magnet would hit the floor before the first magnet.
11. Study the diagram below. The square loop of wire is moved inside the magnetic field from position P to position Q. Discuss the induced *emf* in the loop along each of it edges: **ab**, **bc**, **cd**, **da**. What is the net *emf* for the complete loop? Explain.



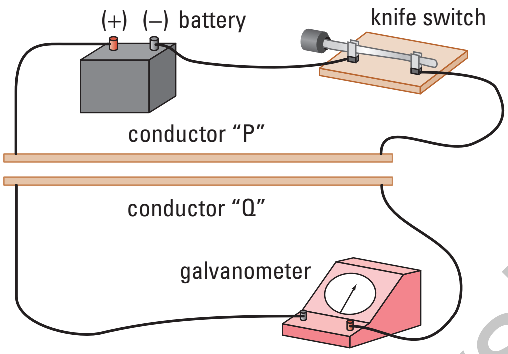
12. A circular copper loop lies in the plane of the page. A magnetic field, which points out of the page, moves downward in the plane of the page so that it passes over the coil from top to bottom. The loop is not inside the field at the beginning or at the end of the motion. Discuss the nature of the induced *emf* in the loop as the field moves across the coil.



13. It has been said that "every motor is a generator". Explain why this is true. Is it also true that "every generator is a motor"? Explain.
14. A copper plate is placed between the poles of an electromagnet. When an AC current flows through the electromagnet, it creates a fluctuating magnetic field between the poles of the magnet. Discuss the effect of the changing magnetic field on the charges in the copper plate.



15. The diagram below shows two conductors, P and Q, side by side. Describe the induced current in the conductor Q, connected to the galvanometer, when the switch connecting the conductor P to the battery is closed. Does the induced current in conductor Q flow to the left or to the right? Explain how to find the direction of induced current using right-hand rule for (a) the generator effect and (b) Lenz's law.



16. Explain the difference between the way the right-hand rule is applied for the generator effect and for Lenz's law.

Making Connections

17. A 24 V DC motor runs at a speed of 3 600 rpm. At that speed, it draws 1.0 A from the battery. The resistance of the coil, measured when the motor is at rest, is found to be 6.0 Ω. Explain why the motor does not draw a current of 4.0 A when it is running. Evaluate the dangers of running at speeds much lower than its ideal operating speed.
18. Cable companies transmit their signals over coaxial cables. This type of conductor is very costly compared to regular conductors composed of two strands of wire running side by side, as in a household extension cord. Investigate to find out why the cable company uses the more costly coaxial cable.

Problems for Understanding

19. The power rating for a transformer is 6.00×10^3 W. The current to the primary coil of the transformer is 1.20×10^2 A and the secondary voltage is 2.00×10^3 V. What is the ratio of the number of turns in the primary coil to the number of turns in the secondary coil? Assume the efficiency is 100%.
20. A 1.50×10^3 W step-up transformer has a 250 turns in its primary coil and 4000 turns in its secondary coil. The primary voltage is 60.0 V.
    - **(a)** What is the current in the primary coil?
    - **(b)** What is the voltage output at the secondary coil?
    - **(c)** If the efficiency of the transformer is 100%, what is the current output at the secondary coil?
    - **(d)** If the efficiency of the transformer is 97.5%, what is the power available at the secondary coil?
    - **(e)** What is the current available at the secondary coil in part (d)?
21. A transformer runs at 95.7% efficiency. The potential difference at its primary coil is 1.60×10^2 V. The potential difference at its secondary coil is 6.40×10^3 V. The resistance of the primary coil is 0.500 Ω.
    - **(a)** What is the power input at the primary coil?
    - **(b)** What is the power output at the secondary coil?
    - **(c)** If the secondary coil has 12 000 turns, how many turns has the primary coil?
    - **(d)** At what rate is heat being produced in the transformer?
    - **(e)** What is the current available at the secondary coil?

Numerical Answers to Practice Problems

1. 120 turns **2.** 1.60×10^3 V **3.** $I_1 = 960$ A, $I_2 = 2.40$ A, $I_S = 1.92 \times 10^3$ A **4.** $I_S = 8.3 \times 10^3$ A

UNIT 5 PROJECT

Building a Better Motor

Background

Electric energy powers most of the gadgets used by our mechanized society. An electric motor is the result of the interaction between electric current and magnetic fields. In this activity, you will design and build an electric motor. Then you will create a marketing brochure to sell your product.

Challenge

Part 1: A Motor That Works

In this first part, you must simply *construct a motor that works*.

Part 2: Design a Better Motor

In the second part, you will redesign your motor. Select new materials and a design structure to construct a motor specifically designed to comply with, and compete in, one or more of the following categories.

- Fastest/slowest continually spinning motor
- Most reliable motor
- Smallest/largest functioning motor
- Motor requiring the least amount of current or voltage to operate
- Most creative overall design

Materials

- strips of Plexiglas™ (20 cm x 3 cm)
- 1/4 inch dowelling (10 cm in length)
- 2 sewing pins
- 1.0 m thin-gauge enamelled wire (36 gauge or smaller)
- empty bathroom-tissue roll
- heat gun
- drill and 1/4 inch drill bit
- sandpaper
- 24-gauge insulated electrical wire

Safety Precautions

- Observe caution whenever working with electric energy.
- Wear appropriate protective gloves when heating the Plexiglas™.

  Note: Hot Plexiglas™ looks just like cold Plexiglas™.

Design Criteria

As a class, establish guidelines and requirements for the marketing brochure. Include

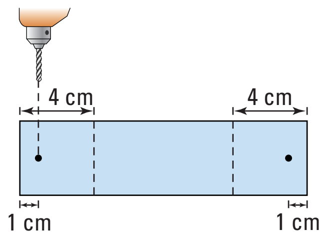
- a design blueprint of your finished product
- the category for which you are designing your motor
- a list of design improvements

Design a rubric to organize these guidelines to be used for assessment.

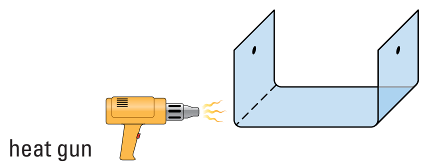
Action Plan

Part I

1. To build the base, drill a hole in each end of the Plexiglas™ strip.



2. Carefully heat the Plexiglas™ along the dotted line drawn 4 cm from each end. Heat one end at a time, bending the Plexiglas™ to 90°.

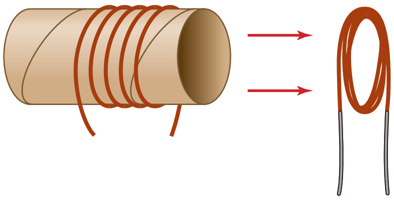


ASSESSMENT

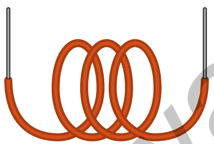
After you complete this project:

- **assess yourself based on how well your motor fits the criteria for which it was designed**
- **assess your technical skills during the construction phase to see if you improve**
- **use the rubric to assess your communication skills demonstrated in your brochure**

3. To build the coil, measure 1.0 m of the thin-gauge wire. Use sandpaper to sand the last 4.0 cm from both ends of the coil wire to remove the enamel.
4. Wrap the wire tightly around the tissue-paper roll. Remove the wire coil from the roll.



5. To build the commutators, cut two 15 cm lengths of the 24-gauge insulated wire. Carefully strip 2.0 cm of insulation off each end.
6. Individually wrap each wire strip around a pencil, leaving 4 cm unwound at each end.



7. Assembly: carefully glue the coil onto the wooden dowelling, ensuring that each sanded portion of wire runs down the length of the dowelling. Ensure that the wires are directly across from one another. Avoid getting glue on the sanded lengths of wire.
8. Carefully insert a pin into each end of the dowelling.
9. Place the pins and dowelling into the Plexiglas™ support as shown below.

10. Carefully glue the commutators into position, ensuring that they each make simultaneous contact, each with a different side of the sanded ends of the coil wire.
11. To make it go, place the coil in a large magnetic field.
12. Connect a direct current power supply to the free commutator ends. Turn on the power supply and watch your motor spin.

Part 2

Choose a category to compete in. Improve the original design, and tailor your motor to meet the specific criteria. You are encouraged to use different materials and structural layouts. Keep a log of design ideas. Include an explanation of how you solved any problems that you encountered.

Evaluate

1. Assess the success of your original motor. Does it operate continuously when activated?
2. Assess your technical effectiveness during the designing phase of this investigation. What skills and knowledge allowed you and your partner to accomplish the task? What aspects hindered your accomplishments?

UNIT 5 Review

Knowledge and Understanding

True/False

In your notebook, indicate if each statement is true or false. Correct each false statement.

1. All magnets have both an N-pole and an S-pole.
2. A circular coil of wire contains three turns. When a current is flowing through the coil, the adjacent turns of wire repel each other.
3. The total power output of a parallel circuit is the sum of the power outputs of the individual loads.
4. The terminal voltage of a battery is lower than its *emf*, $\mathscr{E}$, because of the internal resistance of the battery.
5. Circuit breakers and fuses protect circuits from an excessive potential difference.
6. A circuit has a single load connected to a battery. If a second load is connected in parallel to the first load, the equivalent resistance of the circuit must decrease.
7. If two equal resistors are in parallel, then the potential difference of the battery must be shared equally between them.
8. When a generator is being used to power a light bulb, increasing the power output (wattage) of the light bulb causes the generator to produce a greater *emf*, $\mathscr{E}$.
9. The magnetic North pole of the Earth is the South-seeking pole of a magnet.

Multiple Choice

In your notebook, write the letter that gives the correct answer to each of the following questions.

10. If a 6.0 Ω and a 24 Ω load are connected in series, then the current in the 6.0 Ω load is:
    - (a) four times the current in the 24 Ω load.
    - (b) the same as the current in the 24 Ω load.
    - (c) one quarter of the current in the 24 Ω load.
    - (d) one half of the current in the 24 Ω load.
11. A circuit consists of two light bulbs connected in parallel with each other. Each branch of the circuit contains a switch connected to the bulb in that branch. If one of the switches is opened, then the other light bulb will:
    - (a) glow with the same light.
    - (b) glow brighter.
    - (c) glow less brightly.
    - (d) burn out.
12. Potential difference is a measure of:
    - (a) the energy available to a current.
    - (b) the energy lost when a current passes through a load.
    - (c) the energy per unit of time.
    - (d) the energy available to a unit of charge.
13. A copper ring lies in the plane of the page. A bar magnet is moving through the ring into the page, with its N-pole pointing away from the viewer. As the magnet moves through the ring, the current in the ring will be:
    - (a) clockwise.
    - (b) counter-clockwise.
    - (c) first clockwise, then counter-clockwise.
    - (d) first counter-clockwise, then clockwise.
14. For a transformer, the ratio of the primary voltage to the secondary voltage (V^P/V^S) can be increased by:
    - (a) increasing the primary voltage.
    - (b) increasing the number of turns in the primary coil.
    - (c) decreasing the number of turns in the primary coil.
    - (d) decreasing the secondary voltage.
15. A conductor carries a current eastward through a magnetic field that points directly upward. The direction of the magnetic force on the conductor is:
    - (a) west
    - (b) east
    - (c) north
    - (d) south
16. Which of the following statements is **not** true for the back *emf* in a motor:
    - (a) The back *emf* depends on the internal resistance of the armature coil.
    - (b) The back *emf* must always be less than the supplied *emf*.
    - (c) The back *emf* exists whenever the motor is running.
    - (d) The back *emf* increases with the speed of the motor.

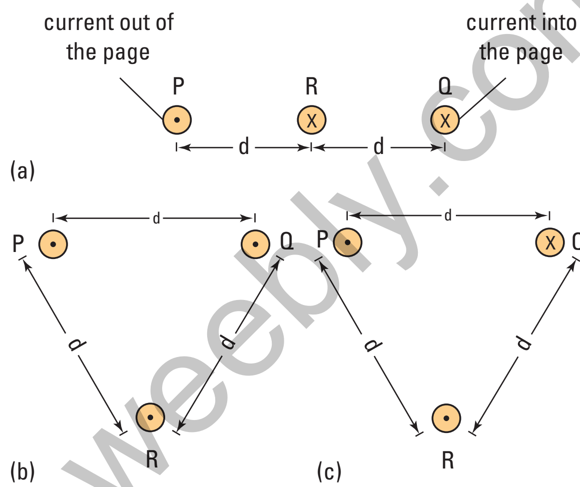
17. Which of the following would **not** be a good material to use as the core of an electromagnet?
   (a) aluminum
   (b) cobalt
   (c) nickel
   (d) iron

18. Two circular coils of wire are placed on a table so that one of the coils lies on top of the other. The current in the lower coil is switched on; it is gradually increased until it is 10 A, and then the current is switched off. The upper coil is connected to a galvanometer. Which of the following statements is true for the current in the upper coil?
   (a) The current in the upper coil is greatest at the instant the current in the lower coil is first turned on.
   (b) The current in the upper coil continues to increase, as long as the current in the lower coil is increased.
   (c) The current in the upper coil flows only when the switch to the lower coil is opened and closed.
   (d) The current in the upper coil is greatest when the current in the lower coil is switched off.

Short Answer

19. Explain the similarities and differences between:
   (a) current and electron flow.
   (b) series and parallel circuits.
   (c) Action-at-a-distance theory and Field theory.
   (d) magnetic north and geographic north.
   (e) Lenz's law and the generator effect.
   (f) diamagnetic and paramagnetic materials.
   (g) the terminal voltage and *emf* of a battery.

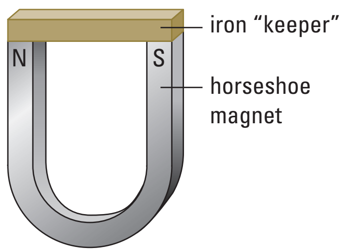
20. The diagram (top right) shows three configurations of three parallel conductors (P, Q and R) that carry currents of equal magnitude in the indicated directions. For each of the conductors, P and Q, identify the direction of the magnetic field that their current creates at the position of conductor R. Then, find the direction of the net magnetic field at the position of conductor R, and identify the direction of the force that conductor R experiences due to the net magnetic field.



21. A light bulb is marked 250 W – 120 V. What is the resistance of its filament? How could you connect this type of bulb to a 240 V source so that it is not damaged by the increased potential?

22. An electric motor is running under a heavy load. You notice that the cover of the motor is getting quite hot. Explain why the motor runs at a relatively cool temperature at high speeds, and why, when it is trying to drive a heavy load, it seems to get hot.

23. When you store a horseshoe magnet, it is recommended that an iron "keeper" be placed across its poles as shown. What is the purpose of the keeper?



Inquiry

24. A voltameter and ammeter are used to measure the potential difference and current for a load. The data taken from the measurements is recorded in the table below.
   (a) Make a graph of the data, so that the slope of the graph can be used to find the resistance of the load.
   (b) What happens to the resistance as the current through the load rises?

Trial	Voltage (V)	Current (A)
1	0	0
2	4	0.6
3	6	0.9
4	8	1.2
5	18	1.7
6	28	1.9
7	40	2.1

25. For a given DC motor, how does the back *emf* depend on the speed (measured in revolutions per minute/RPM) at which the motor is running? First, make a hypothesis that predicts the relationship between these two variables. Then, design an investigation to measure the back *emf* of a DC motor at various speeds. You can only use equipment that would be available in your physics laboratory. A graph of back *emf* versus motor speed should be used to test your hypothesis about the relationship between these two variables.
26. In the Problems for Understanding section, question 38 requests that you calculate the current in a coil from data that relates the magnetic force to the current flowing through it. Create a hypothesis that predicts a relationship between the current in a coil and the force a magnetic field exerts on the edge of the coil that lies in the field. Design an investigation that could be used to test your hypothesis. How could your experiment be used to define the strength of the magnetic field between the poles of the horseshoe magnet?
27. Design an investigation to show how the efficiency of a motor changes when the amount of load it carries is changed.
28. Design and construct a moving coil galvanometer. A moving coil galvanometer is very similar to a miniature electric motor. Investigate the structure of a galvanometer and prepare a report on the similarities and differences between motors and meters. What method is used in electric meters so that the force that the magnetic field exerts on the current in the coil, is applied perpendicularly to the edges of the coil, over the total range of the coil's motion?

Communication

29. Compare the operation of a slip-ring commutator with a split-ring commutator.
30. Explain why the induced *emf* in a coil rotating in a magnetic field alternates in direction.
31. Do magnetic lines of force in a bar magnet have a beginning and an end? What are the implications of your answer with respect to the existence of magnetic monopoles?
32. While electric forces seem to require the existence of electric charges, magnetic forces do not require the existence of magnetic poles. Explain this apparent anomaly.
33. In an electric circuit, explain the difference between the "difference in potential energy" and "potential difference" across a load.
34. Explain why it is illogical to show lines of force in a magnetic field that cross each other?

Making Connections

35. During an experiment with a bar magnet, the magnet falls on a concrete floor several times. As the experiment progresses, it is observed that the strength of the bar magnet is lower than it was at the start of the experiment. Using Domain theory, explain the probable cause of this observation.
36. Investigate the method used to record and read a signal from a magnetic medium, such as used in audio, video or computer disk-drive systems. Using Domain theory, explain how the information is stored. Using Lenz's law, explain how the patterns on the disk drive of a computer interact with the magnetic head of the disk drive when data is read from the disk.
37. Two students are challenged to design and build a transformer to operate a 6 V – 30 W light bulb at a distance of 30 m from the electrical outlet in the laboratory. They have a 30 m extension cord that is made from 18 gauge

wire. First, they build a transformer to step down the voltage from the laboratory's 120 V supply. Having designed and built the transformer, they connect the bulb to the transformer in the laboratory. The bulb glows brightly, confirming that the transformer has been designed and built correctly. They then run the extension cord from the transformer to the bulb, and turn it on. The bulb does not light up. What could be the cause of this failure? Provide numerical analysis to support your argument. How could they adapt their system to make the bulb light properly at a distance of 30 m from the plug-in?

Problems for Understanding

38. A coil, consisting of 600 turns of wire, has an edge that is 5.0 cm long that passes through a magnetic field. The field strength is 0.220 T east, and acts at right angles to the current in the coil. If the force on the coil was 8.25 N down, what was the magnitude and direction of the current in the coil?

39. An immersion heater took 18 minutes to bring one litre of water to boil, when the current through the heater was 6.0 A. How long would it take the heater to bring the same amount of water to a boil, if the current was increased to 18 A? Assume that all the heat from the coil is transmitted to the water.

40. The magnetic field of Earth is about 1.50×10^{-4} T due north. A transmission line carries a current of 120 A. If the distance between two of the supporting towers is 750 m, how much force does the magnetic field from the Earth exert on the current in the line segment between the towers, when the current is due (a) east? (b) south? (**Note:** Remember that force is a vector quantity.)

41. Draw a circuit section that shows how to connect five resistors, each with a resistance of 2.0 Ω, such that the equivalent resistance of the section is (a) 7.0 Ω; (b) 0.40 Ω; (c) 2.5 Ω; (d) 2.4 Ω; (e) 1.0 Ω.

42. A 15 V battery is connected to four resistors. Two resistors, 5.00 Ω and 7.50 Ω, are connected in parallel so that they are in series with resistors of 4.00 Ω and 5.00 Ω. Find the current through each resistor, and the potential drop across each resistor. What is the equivalent resistance of the circuit?

43. A generator has a rectangular coil, consisting of 750 turns of wire, measuring 6.0 cm by 10.0 cm. The coil is placed between the poles of a horseshoe magnet, so that the 10 cm edge is parallel to the face of the magnet. The coil is rotated so that the edges of the coil move past the face of the magnet at a speed of 8.0 m/s. The strength of the magnetic field is 0.0840 T.

(a) What is the maximum induced *emf* in each edge of the coil as it moves past the magnet?

(b) What is the total induced *emf* of the generator?

(c) The coil is made of 22-gauge (measurement missing?) wire; what is its internal resistance?

(d) If the generator is used to supply current to an external circuit with a 25.0 Ω resistance, what current will it provide?

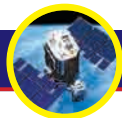
44. A battery has an *emf* of 18 V. When it is connected to an external load with a resistance of 1.5×10^2 Ω, a current of 0.115 A flows.

(a) What is the terminal voltage of the battery?

(b) What is the internal resistance of the battery?

(c) What will be the terminal voltage when the battery is connected to a 25 Ω load?

COURSE CHALLENGE



Space-Based Power

Consider the following as you complete the final information-gathering stage for your end-of-course project:

- Attempt to combine concepts from this unit with relevant topics from previous units.
- Verify that you have a variety of information items including conceptual organizers, useful web sites, experimental data, and unanswered questions to help you create your final assessment product.
- Scan magazines, newspapers, and the Internet for interesting information to validate previously identified content and to enhance your project.

Is space-based power possible?

Space-Based Power?

Consider the following. The world is becoming increasingly technological, and more technology means more energy use. The question about where to turn next for viable non-polluting energy sources is not a new one. It has long been well known that gases from the tailpipes of automobiles and the smokestacks of coal-fired generating stations produce noxious gases, creating smog such as that shown on the following page. Oil and natural gas reserves will not last forever, and they are not a clean source of energy. The arguments for and against use of nuclear energy have been with us for at least 30 years. What are our alternatives? Windmills? In a few places, yes, but certainly not in most. Is the use of fuel cells a partial answer? How far reaching will be the harnessing of ocean wave power to produce energy? Will fusion power be a viable alternative?

ASSESSMENT

After you complete this Challenge, you will be assessed as follows on:

- **the quality of your research**
- **the presentation**
- **other criteria you decide upon, as a class**

A thick brown haze of smog engulfs a city, the result of incomplete combustion from hydrocarbon fuels.

A radical new idea has been proposed to help meet the ever-increasing need for energy — one that will not negatively affect Earth's environments. The proposal is for the use of space-based power. Could an orbiting satellite capture solar energy before it is diffused by the atmosphere, convert it into microwaves to be beamed to a receiving station on Earth, and from there be transformed into useable electric power? The idea sounds as if it comes from a science-fiction novel. Yet, the concept for such a system is currently under active investigation around the world.

A space-based power delivery system requires the integration of a number of different emerging technologies. Look at just a few of the needs that must be met:

In Space

- Satellites in geosynchronous orbit with photovoltaic panels
- Power-conversion components to convert the electricity from the panels to microwave radiation
- Transmitting antennas to direct microwave beams to Earth

On Earth

- Receiving antennas (called rectennas) to capture the incoming microwaves and convert them into electricity that can be used
- Power-conversion components to convert the direct current (DC) output from the rectennas to alternating current (AC) which is compatible with local electrical grids

Power Reliability

- Power-conversion efficiencies for all weather conditions

Think about these needs as you plan for the Challenge.

Math Link

Only about 5×10^{-8} % of the total energy emitted by the Sun reaches Earth's surface. Try to calculate this value by making appropriate assumptions. The necessary data and equations are provided on the inside front and back covers.

Challenge

Develop and present a case either for or against the use of **space-based power** as a major source of energy to power Earth's technologies in the future. You will use knowledge of concepts investigated throughout this course, and additional research outside this resource, to develop your presentation about the feasibility of space-based power for widespread future use. Your class will together decide whether the presentations will be made:

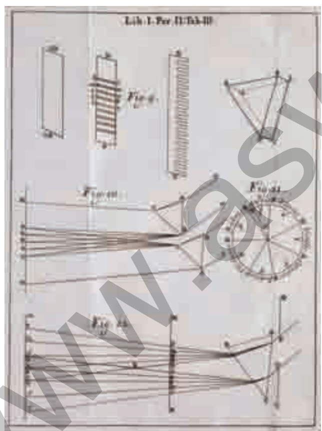
- through a formal debate
- through role-play
- through research report presentations (either as a written report, an audiovisual presentation, or a poster presentation to an international commission (or to another group you decide upon)
- through another format of your choice

Materials

All presentations must be supported by your portfolio of research findings, the results of supporting experiments conducted, and a complete bibliography of references used. Other materials will be considered under the heading Design Criteria.

PHYSICS FILE

The rough notes of many famous scientists are now treasured artifacts, not only for their scientific value, but also for the window they offer into each scientist's mind and way of thinking. This page shows the jottings of one such thinker, Isaac Newton.



Design Criteria

A. You need to develop a system to collect and organize information that will include data, useful formulas, and even questions that you use to formulate your final recommendation near the end of the course. You can collect your own rough notes in your Physics Research Portfolio (print or electronic).

B. Building a Physics Research Portfolio
Your individual creativity will shape the amount, the type, and the organization of the material that will eventually fill your portfolio. Do not limit yourself to the cues scattered throughout the text; if something seems to fit, include it.

Suggested items for your Physics Research Portfolio:

- experiments you have designed yourself, and their results
- useful formulas
- specific facts
- interesting facts
- disputed facts
- conceptual explanations
- diagrams
- graphical organizers
- useful page numbers
- useful web sites
- experimental data
- unanswered questions

C. As a class, decide on the type(s) of assessment you will use for your portfolio and for its presentation. Working with your teacher and classmates, select which type of presentations you will use (debate, role-play, or research presentation, as outlined previously) to present your space-based power findings.

Action Plan

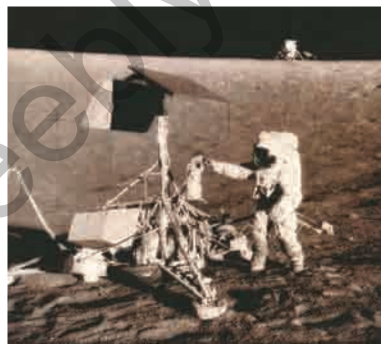
1. As a class, have a brainstorming session to establish what you already know about current and possible future energy sources. For example, what are the different energy sources used around the world today, and what are the pros and cons of each of them? Why is it important to look for alternatives?
2. As a class, design a rubric or rubrics for assessing the task. (You may decide to assess facets of the challenge leading up to the presentation, as well as the presentation itself.)
3. Decide on the groupings, or assessment categories, for this task.
4. Familiarize yourself with what you need to know about the task that you chose. For example, if it's a debate, it is important to research the proper rules for debating in order to carry out the debate effectively.
5. Develop a plan to find, collect, and organize the information that is critical to your presentation and the information you record in your Physics Research Portfolio.
6. Carry out the Course Challenge recommendations that are interspersed throughout the text wherever the Course Challenge logo and heading appear, and keep an accurate record of these in your portfolio.
7. When researching concepts, designing experiments, or following a cued suggestion in the text, the McGraw-Hill Ryerson web site is a good place to begin: *www.school.mcgrawhill.ca/resources/*
8. Carry out your plan and make modifications throughout the course as necessary.
9. Present your case to your class. Review each presentation and identify Space-Based Power Supporters and their reasons, as well as Space-Based Power Opposers and their reasons.

Evaluate Your Challenge

1. Using the rubric or rubrics you have prepared, evaluate your work and presentation. How effective were they? Were others able to follow the evidence, results, and conclusions you presented? If not, how would you revise your presentation.
2. Evaluate Course Challenges presented by your classmates.
3. After analyzing the presentations of your classmates, what changes would you make to your own project if you were to have the opportunity to do it again? Provide reasons for your proposed changes.
4. How did the organization of information for this challenge help you to think about what you have learned in this course?

Space Link

The Moon offers a wealth of amorphous silicon. Some supporters of space-based power foresee constructing a photovoltaic manufacturing plant on the moon. Mining the resources of the Moon is an issue of feasibility, but it is also an issue of politics and ownership. In your opinion, what is the likelihood of a Moon-mining plan proceeding if it is contrary to global political will?



Background Information

The following information will give you some idea of the questions you should consider as you try to decide if this proposal is one that you would support or not support in your presentation. A great deal of evidence can come from your studies and investigations throughout this course. Some of the major issues are:

- How will the satellite get into orbit?
- How high should the satellite be?
- How feasible is wireless energy transmission?
- How safely can the beam be focussed?
- How much will it cost?

The following sections give you "fuel for thought." They are tied closely to Course Challenge cues in your text so that you may start to develop your plans for this culminating Course Challenge at an early stage in your course.

Getting into Orbit

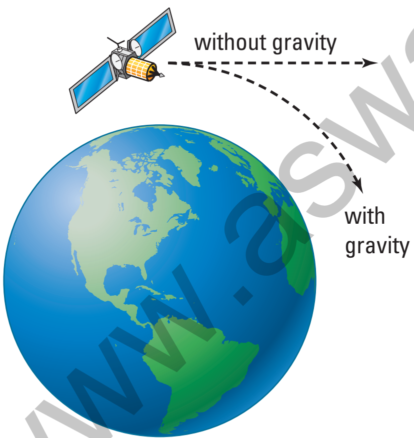
How fast does an object need to travel to get into orbit around our Earth? Does the amount of speed that a rocket attains determine both the height and shape of the orbit it will trace out? Space-based power schemes need to be able to capture sunlight and then beam the energy as microwaves to a specific spot on Earth. (See Chapter 2, page 30.)

Staying in Orbit

A satellite, beaming energy in the form of microwaves to Earth, must have an unobstructed "line of sight" to both the sun and the receiving station on Earth. (See Chapter 3, page 104.)

What Does "Weightless" Mean?

Weight refers to the force of gravity acting on an object near the surface of a planet or star. If astronauts were not under the influence of Earth's gravity, they would fly off in a straight line into space. Therefore, astronauts are not weightless; but their weight (the force of gravity pulling them toward Earth) is what keeps them in orbit. Is it possible for astronauts to use a spring scale to weigh themselves as they move around in Earth's orbit? (See Chapter 4, page 140.)



Astronauts and satellites are not "weightless" when in orbit. Their "weight" continually causes them to fall toward Earth.

Staying in Orbit

"A satellite in motion will stay in motion unless acted on by an external force." Or will it? In Chapter 2, you applied your understanding of motion to an information-gathering investigation of satellites and their orbits. A satellite has mass, perhaps a great deal of mass, and therefore has inertia. Once in orbit, what forces will act on the satellite? What will be required to keep it in a geosynchronous orbit? (See Chapter 4, page 159.)

The Cost of Altitude

Space Shuttle launches are regular occurrences, as the shuttle is the main supply vehicle for the International Space Station. Newton's 2nd law accurately predicts that the more mass that is to be sent into orbit, the greater the force that will be required. Generating this force requires rocket engines and plenty of fuel. A major drawback of any concept that involves putting objects or people into space is the cost required to generate enough acceleration to put the mass into orbit. (See Chapter 4, page 160.)

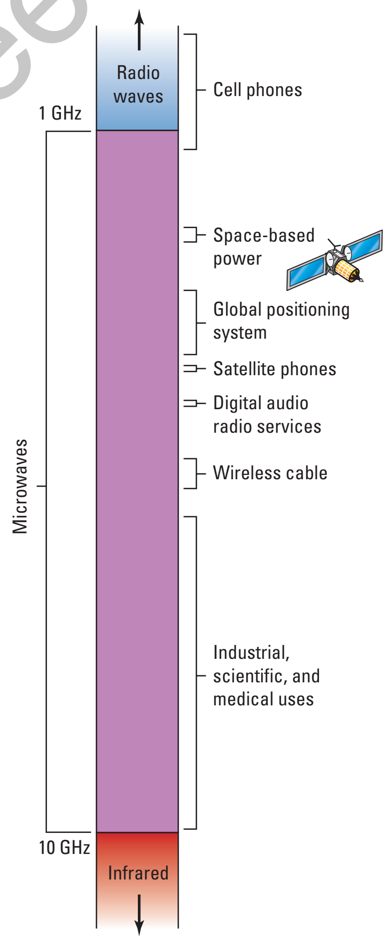
Safety concerns surrounding life near a receiving antenna must be investigated.

Does It Really Work?

Wireless transmission of power has been experimentally verified. However, several challenges still exist. The first law of thermodynamics predicts that any energy transformation system developed will not be 100% efficient. Also, energy is required to fabricate the materials and equipment used to build the satellite and earthbound receiving station. (See Chapter 6, page 313.)

Wave Frequency, Energy and Safety

How much energy can microwaves carry? Can it be dangerous to human, animal or plant life? Microwaves, part of the electromagnetic spectrum, carry energy from space to Earth. Max Plank (1858–1947) suggested that the energy contained within electromagnetic radiation was related to the radiation frequency multiplied by a constant (now called Plank's constant $h = 6.63 \times 10^{-34}$ J · s). Use Plank's energy relationship, $E = hf$, to investigate the energy differences between green light ($f = 5 \times 10^{-14}$ Hz), heat or infrared radiation ($f = 4 \times 10^{12}$ Hz), and microwaves ($f = 6 \times 10^{9}$). (See Chapter 7, page 337.)



Microwaves, the portion of the electromagnetic spectrum between Radio waves and Infrared, are used in a variety of applications.

Interference: Communication Versus Energy Transmission

Microwaves make up a large part of the electromagnetic spectrum with frequencies ranging from about 10^{11} to 10^{9} Hz. The microwave part of the electromagnetic spectrum has been divided into small "bandwidths" for communication applications — from everyday cell phones and TV to military and space purposes. The sheer number of required bandwidth requirements has caused very tight spacing of some microwave frequencies. Signals received by an antenna from more than one source may cause effects similar to the interference patterns of superposition you saw during your study of springs. (See Chapter 7, page 335.)

Intensity and Power Density

Sound intensity we can hear, but what about microwave intensity? Sound intensity is sometimes given in picowatts per square metre. Health Canada standards state that exposure to 5.85 GHz microwaves is safe if the power density is below 10 W/m^2. How much land or water area will a receiving station require to be able to provide power to a community without endangering its nearby inhabitants? (See Chapter 8, page 377.)

PHYSICS FILE

Astronomers at NASA once asked physicist Freeman Dyson to describe what an advanced civilization might look like. The physicist's answer points to the power of the Sun. He said:

"I cannot tell you what an advanced civilization would look like, because they may choose to live in unpretentious circumstances. I can tell you what an advanced technology would look like. They would almost certainly have enclosed their Sun to harvest most of its energy. All that would be left for distant viewers to see would be an infrared emitter with little visible light."

We're Losing Power

Actually, it is not power but energy that is lost. Beaming microwaves through the atmosphere is not 100% efficient. Space-based power requires an understanding of both the wave theory and the particle theory of light. The energy loss will cause the atmosphere and surrounding area to heat up. (This effect could be used to assist in aquaculture (fish farming) if a receiving station were placed on water.) (See Chapter 10, page 466.)

Keeping the Mirror Clean

The land-based systems that focus light for solar thermal energy facilities on Earth are restricted by day-night cycles and bad weather. Some space-based power proposals suggest using parabolic mirrors to concentrate the solar radiation onto very specialized and efficient photovoltaic cells. Other systems would use larger panels of cheaper photovoltaic cells, removing the need for a parabolic reflector. The cheaper cells could be made from raw materials found on the moon! (See Chapter 10, page 488.)

From the Equator to the Poles

The ray model of light provides a very accurate method of predicting the location of images. The same process can be used to predict how the microwave beam from the satellite will strike Earth's surface at various locations. Vacationing somewhere near the equator demands much more attention to your sun block and sunlight exposure time than a destination closer to the poles. The reason lies with Earth's shape and the linear propagation of light. (See Chapter 10, page 478.)

Photovoltaic Alternatives

Type	Efficiency	Advantage	Application
specialized cells made from various materials	30%	can receive concentrated light focussed by several reflectors	selected locations experiencing a great deal of direct sunlight
single crystal silicon	25%	durable and long lived	satellites and industry
ploy-crystalline silicon	18%	easily deposited on glass or metal surfaces; flexible cells	small scale power generation, e.g., cottages, roadway signs
amorphous silicon	10%	easily manufactured inexpensive	calculators

Twinkling Stars Point to a Problem

Your eyes bend light, focussing an image onto your retina. If the image is blurred, corrective lenses can help. The atmosphere's continually changing density also refracts light. Stars twinkle and hot roadways shimmer due to atmospheric refraction. Unlike eyeglass lenses, the atmosphere is always changing — air temperature, pressure, and moisture content changes cause dramatic shifts in the atmospheric index of refraction. How reliably will engineers be able to focus the energy beam onto the receiving antenna? (See Chapter 11, page 517.)

Free Energy?

Solar-powered calculators, street signs, and office buildings take advantage of the unique characteristic of semiconductor materials, such as silicon. Shining sunlight on semiconductors can generate an electric current. A space-based power system captures and converts sunlight into electric energy through the use of semiconducting photovoltaic cells. The electric energy is transformed into microwaves that are beamed to Earth where they are transformed back into useable electric energy. (See Chapter 13, page 615.)

How Much Electric Power?

How much electric energy does a small town require in a day? You have investigated various aspects of a space-based power system. Now, it is time to investigate the feasibility of such a system in terms of power. (See Chapter 13, page 653.)

Wrap Up

These ideas are provided to help you develop your case either for or against space-based power. You will doubtless come up with many other ideas of your own for consideration, giving your presentation its own unique characteristics.

This brief tour has included some of the factors to consider about space-based power as a possible future energy source, as well as ideas about your own presentation of a case for or against it.

We are living during a time when scientific knowledge and technology may together provide important solutions to global energy needs. The potential for sustainable power production by using a variety of energy sources has only recently become possible. Today, new choices can be considered because of advancement in technology and deeper scientific understanding of our world, from the nature of ecosystems to the operation of rockets. Your own thorough investigation of this one possible energy source — solar-based power — will give you a better understanding of how it may or may not be a viable alternative to energy sources currently being used.

PHYSICS FILE

Alternative energy sources, such as wind-based power, are often criticized for occupying large areas of land. Space-based power greatly reduces this problem by placing photovoltaic panels in orbit. The receiving antennas, however, still require sizable portions of land. There are cost and logistical problems associated with constructing a receiving antenna in a remote region, such as the desert shown below. However, unlike hydro-electric and wind-power installations, the location of the antenna is not dependent on geographic features. Rather, it can be placed in a location that takes into consideration environmental and other factors.

Precision, Error, and Accuracy

A major component of the scientific inquiry process is to compare experimental results with predicted or accepted theoretical values. In conducting experiments, you must realize that all measurements have a maximum degree of certainty, beyond which there is uncertainty. The uncertainty, often referred to as error, is not a result of a mistake but rather, it is caused by the limitations of the equipment or the experimenter. The best scientist, using all possible care, could not measure the height of a doorway to a fraction of a millimetre accuracy using a metre stick. The uncertainty introduced through measurement must be communicated using specific vocabulary.

(a) (b) (c)

Differentiating between accuracy and precision

Experimental results can be characterized by both their accuracy and their precision.

Precision describes the exactness and repeatability of a value or set of values. A set of data could be grouped very tightly, demonstrating good precision, but not necessarily be accurate. The darts in Figure **A**, above, miss the bull's-eye and yet are tightly grouped, therefore demonstrating precision without accuracy.

Accuracy describes the degree to which the result of an experiment or calculation approximates the true value. The darts in Figure **B**, above, miss the bull's-eye in different directions, but are all relatively the same distance away from the centre. The darts demonstrate three throws that share approximately the same accuracy, with limited precision.

The darts in Figure **C**, above, demonstrate accuracy and precision.

Random Error

- Random error results from small variations in measurements due to randomly changing conditions (weather, humidity, equipment, level of care, etc.).
- Repeating trials will reduce but never eliminate random error.
- Random error is unbiased.
- Random error affects precision.

Systematic Error

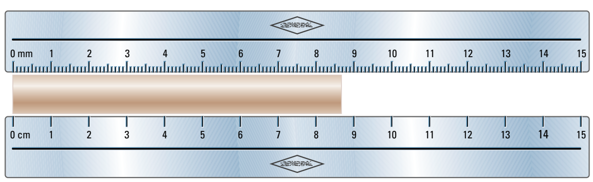
- Systematic error results from consistent bias in observation.
- Repeating trials will not reduce systematic error.
- Three types of systematic error are: natural errors, instrument-calibration error, and personal error.
- Systematic error affects accuracy.

Error Analysis

Error exists in every measured or experimentally obtained value. The error could deal with extremely tiny values such as wavelengths of light or with large values such as the distances between stars. A practical way to illustrate the error is to compare it to the specific data as a percentage.

Relative Uncertainty

Relative uncertainty calculations are used to determine the error introduced by the natural limitations of the equipment used to collect the data. For instance, measuring the width of your textbook will have a certain degree of error due to the quality of the equipment used. This error, termed **estimated uncertainty**, has been deemed by the scientific community to be half of the smallest division of the measuring device. A metre stick with only centimetres marked would have an error of ±0.5 cm. A ruler that includes millimetre divisions would have a smaller error of ±0.5 mm. The measure should be recorded showing the estimated uncertainty, such as 21.00 ±0.05 cm. Use the relative uncertainty equation to convert the estimated uncertainty into a percentage of the actual measured value.



Estimated uncertainty is accepted to be half of the smallest visible division. In this case, the estimated uncertainty is ±0.5 mm for the top ruler and ±0.5 cm for the bottom ruler.

$$\text{relative uncertainty} = \frac{\text{estimated uncertainty}}{\text{actual measurement}} \times 100\%$$

Example:

Converting the error represented by 21.00 ±0.05 cm to a percentage.

$$\text{relative uncertainty} = \frac{0.05\ \cancel{\text{cm}}}{21.00\ \cancel{\text{cm}}} \times 100\%$$
$$= 0.2\%$$

Percent Deviation

Frequently, in conducting experiments, it is unreasonable to expect that accepted theoretical values can be verified because of the limitations of available equipment. In such cases, percent deviation calculations are made. For instance, the standard value for acceleration due to gravity on Earth is 9.8 m/s^2 towards the centre of Earth in a vacuum. Conducting a crude experiment to verify this value may yield a value of 9.6 m/s^2. This result deviates from the accepted standard value. It is not necessarily due to error. The deviation, as with most high-school experiments, may be due to physical differences in the actual lab (for example, the experiment may not have been conducted in a vacuum). Therefore, deviation is not necessarily due to error; it may be the result of experimental conditions that should be explained as part of the error analysis. Use the percent deviation equation to determine how close the experimental results are to the accepted or theoretical value.

$$\text{percent deviation} = \left| \frac{\text{experimental value} - \text{theoretical value}}{\text{theoretical value}} \right| \times 100\%$$

Example:

percent deviation

$$\frac{|9.6\ \cancel{\text{m/s}^2} - 9.8\ \cancel{\text{m/s}^2}|}{9.8\ \cancel{\text{m/s}^2}} \times 100\%$$

$$\text{percent deviation} = 2\%$$

Percent Difference

Experimental inquiry does not always involve an attempt at verifying a theoretical value. For instance, measurements made in determining the width of your textbook do not have a theoretical value based on a scientific theory. There still may exist, however, a desire to determine how precise your measurements were. Suppose you measured the width 100 times and found that the smallest width measurement was 20.6 cm, the largest was 21.4 cm, and the average measurement of all 100 trials was 21.0 cm. The error contained within your ability to measure the width of the text can be estimated using the percentage difference equation.

$$\text{percentage difference} = \frac{\text{maximum difference in measurements}}{\text{average measurement}} \times 100\%$$

Example:

percentage difference

$$= \frac{(21.4\ \cancel{\text{cm}} - 20.6\ \cancel{\text{cm}})}{21.0\ \cancel{\text{cm}}} \times 100\%$$
$$= 4\%$$

SET 1 Skill Review

1. In Sèvres France, a piece of platinum is kept in a vacuum under lock and key. It is the standard kilogram with mass 1.0000 kg. Imagine you were granted the opportunity to experiment with this special mass, and obtained the following data: 1.32 kg, 1.33 kg, and 1.31 kg. Describe your results in terms of precision and accuracy.
2. You found that an improperly zeroed triple-beam balance affected the results obtained in question 1. If you used this balance for each measure, what type of error did it introduce?
3. Describe a fictitious experiment with obvious random error.
4. Describe a fictitious experiment with obvious systematic error.
5. **(a)** Using common scientific practice, find the estimated uncertainty of a stopwatch that displays up to a hundredth of a second.

   (b) If you were to use the stopwatch in part (a) to time repeated events that lasted less than 2.0 s, could you argue that the estimated uncertainty from part (a) is not sufficient? Explain.

Rounding, Scientific Notation, and Significant Digits

When working with experimental data, follow basic rules to ensure that accuracy and precision are not either overstated or compromised. Consider the 100 m sprint race. Several people using different equipment could have timed the winner of the race. The times may not agree, but may all be accurate within the capability of the equipment used.

Sprinter's Time with Different Devices

Time (s)	Estimated error of device (s)	Device
11.356	± 0.0005	photogate timer
11.36	± 0.005	digital stopwatch
11.4	± 0.05	digital stopwatch
11	±0.5	second hand of a dial watch

Using the example of the 100 m race, you will solidify ideas you need to know about exact numbers, number precision, number accuracy, and significant digits.

Exact Numbers If there were eight competitors in the race, then the number 8 is considered to be an exact number. Any time objects are counted, number accuracy and significant digits are not involved.

Number Precision If our race winner wants a very precise value of her time, she would want to see the photogate result. The electronic equipment is able to provide a time value accurate to 1/1000th of a second. The time recorded using the second hand on a dial watch is not able to provide nearly as precise a value.

Number Accuracy and Significant Digits The race winner goes home to share the good news. She decides to share the fastest time with her family. What timing method does she share? She would share the 11 s time recorded using the second hand of a dial watch. All of the other methods provide data that has her taking a longer time to cross the finish line. Is the 11 s value accurate?

The 11 s value is accurate to within ±0.5 s, following common scientific practice of estimating error. The 11.356 s time is accurate to within 0.0005 s. The photogate time is simply more precise. It would be inaccurate to write the photogate time as 11.35600 s. In that case, you would be adding precision that goes beyond the ability of the equipment used to collect the data, as the photogate method can measure time only to the thousandths of a second. Scientists have devised a system to help ensure that number accuracy and number precision are maintained. It is a system of significant digits. *Significant digits* require that the precision of a value does not exceed either (a) the precision of the equipment used to obtain it or (b) the least precise number used in a calculation to determine the value. The table on the left provides the number of significant digits for each measurement of the sprinter's times.

There are strict rules used to determine the number of significant digits in a given value.

When Digits Are Significant ✔

1. All non-zero digits are significant. (159 – three significant digits)
2. Any zeros between two non-zero digits are significant. (109 – three significant digits)
3. Any zeros to the right of *both* the decimal point and a non-zero digit are significant. (1.900 – four significant digits)
4. All digits (zero or non-zero) used in scientific notation are significant.

When Digits Are Not Significant ✘

1. Any zeros to the right of the decimal point but preceding a non-zero digit are not significant; they are placeholders. For example: 0.00019 kg = 0.19 g (two significant digits)
2. Ambiguous case: Any zeros to the right of a non-zero digit are not significant; they are placeholders. (2500 – two significant digits) If the zeros are intended to be significant, then scientific notation must be used, for example: 2.5×10^3 (two significant digits) and 2.500×10^3 (four significant digits).

Calculations and Accuracy As a general rule, accuracy is maintained though mathematical calculations by ensuring that the final answer has the same number of significant digits as the least precise number used during the calculations.

Example:

Find the product of these lengths:
12.5 m 16 m 15.88 m

Product = 12.5 m × 16 m × 15.88 m
Product = 3176 m^3

Considering each data point, notice that 16 has only two significant digits, therefore the answer must be shown with only two significant digits.

Total length = 3.2×10^3 m (two significant digits)

Rounding to Maintain Accuracy It would seem that rounding numbers would introduce error, but in fact, proper rounding is required to help maintain accuracy. This point can be illustrated by multiplying two values with differing numbers of significant digits. As you know, the right-most digit in any data point contains some uncertainty. It follows that any calculations using these uncertain digits will yield uncertain results.

> Multiply 3**2** and 13.5**5**. The last digit, being the most uncertain, is highlighted.
>
> 13.5**5**
> × 3**2**
> **2710** Each digit in this line is obtained using an uncertain digit.
> 406**5** In this line only the 5 is obtained using uncertain digits.
> 4**33.60**
>
> The product 4**33.60** should be rounded so that the last digit shown is the only one with uncertainty.
> Therefore: 4.**3** × 10^2

Notice that this value contains two significant digits, which follows the general rule.

Showing results of calculations with every digit obtained actually introduces inaccuracy. The number would be represented as having significantly more precision than it really has. It is necessary to round numbers to the appropriate number of significant digits.

Rounding Rules When extra significant digits exist in a result, rounding is required to maintain accuracy. Rounding is not simply removing the extra digits. There are three distinct rounding rules.

1. **Rounding Down**
   When the digits dropped are less than 5, 50, 500, etc., the remaining digit is left unchanged.

   Example:
   4.123 becomes
   4.12 rounding based on the "3"
   4.1 rounding based on the "23"

2. **Rounding Up**
   When the digits dropped are greater than 5, 50, 500, etc., the remaining digit is increased or rounded up.

   Example:
   4.756 becomes
   4.76 rounding based on the "6"
   4.8 rounding based on the "56"
   8.649 becomes
   8.65 rounding based on the "9"
   8.6 rounding based on the "49"

3. **Rounding with 5, 50, 500, etc.**
   When the digits dropped are exactly equal to 5, 50, 500, etc., the remaining digit is rounded to the *closest even number*.

   Example:
   4.850 becomes
   4.8 rounding based on "50"
   4.750 becomes
   4.8 rounding based on "50"

Always carry extra digits throughout a calculation, rounding only the final answer.

Scientific Notation Numbers in science are sometimes very large or very small. For example the distance from Earth to the Sun is approximated as 150 000 000 000 m and the wavelength of red light is 0.000 000 65 m. Scientific notation allows a more efficient method of writing these types of numbers.

- Scientific notation requires that a single digit between 1 and 9 be followed by the decimal and all remaining significant digits.
- The number of places the decimal must move determines the exponent.
- Numbers greater than 1 require a positive exponent.
- Numbers less than 1 require a negative exponent.
- Only significant digits are represented in scientific notation.

Example:

1 5 0 0 0 0 0 0 0 0 0 0 0 . becomes 1.5×10^{11}m

0.0 0 0 0 0 0 0 6.5 becomes 6.5×10^{-7}m

continued ►

Skill Set 2 continued from previous page

SET 2 Skill Review

1. There are a dozen apples in a bowl. In this case, what type of number is 12?
2. Put these numbers in order from most precise to least precise.
   (a) 3.2, 5.88, 8, 8.965, 1.000 08
   (b) 6.22, 8.5, 4.005, $1.2000 \times 10 - 8$
3. How many significant digits are represented by each value?
   (a) 215
   (b) 31
   (c) 3.25
   (d) 0.56
   (e) 1.06
   (f) 0.002
   (g) 0.006 04
   (h) 1.250 000
   (i) 1×10^6
   (j) 3.8×10^4
   (k) 6.807×10^{58}
   (l) 3.000×10^8
4. Round these values to two significant digits.
   (a) 1.23
   (b) 2.348
   (c) 5.86
   (d) 6.851
   (e) 6.250
   (f) 4.500
   (g) 5.500
   (h) 9.950
5. Complete the following calculations. Provide the final answer to the correct number of significant digits.
   (a) 2.358×4.1
   (b) $102 \div 0.35$
   (c) $2.1 + 5.88 + 6.0 + 8.526$
   (d) $12.1 - 4.2 - 3$
6. Write each of the following in scientific notation.
   (a) 2.5597
   (b) 1000
   (c) 0.256
   (d) 0.000 050 8
7. Write each value from question 6 in scientific notation accurate to three significant digits.

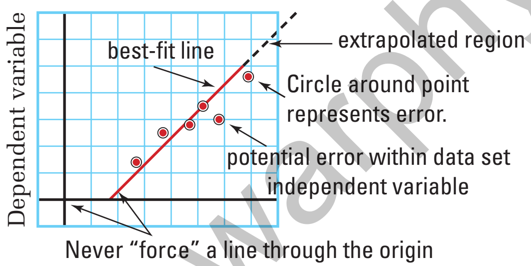
Drawing and Interpreting Graphs

Graphical analysis of scientific data is used to determine trends. Good communication requires that graphs be produced using a standard method. Careful analysis of a graph may reveal more information than the data alone.

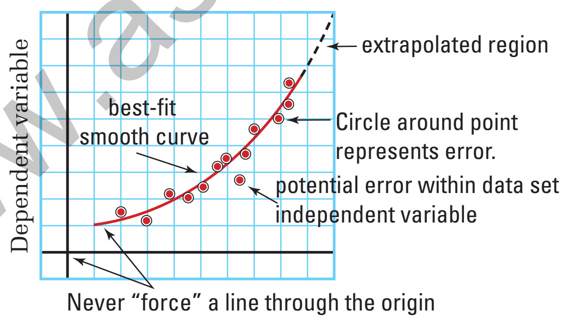
Standards for Drawing a Graph

- Independent variable is plotted along the horizontal axis (include units).
- Dependent variable is plotted along the vertical axis (include units).
- Decide whether the origin (0, 0) is a valid data point.
- Select convenient scaling on the graph paper that will spread the data out as much as possible.
- A small circle is drawn around each data point to represent possible error.
- Determine a trend in the data — draw a best-fit line or best-fit smooth curve. Data points should never be connected directly when finding a trend.
- Select a title that clearly identifies what the graph represents.

Constructing a linear graph



Constructing a non-linear graph



Interpolation and Extrapolation

A best-fit line or best-fit smooth curve that is extended beyond the size of the data set should be shown as a dashed line. You are extrapolating values when you read them from the dashed line region of the graph. You are interpolating values when you read them from the solid line region of the graph.

Find a Trend

The best-fit line or smooth curve provides insight into the type of relationship between the variables represented in a graph.

A *best-fit line* is drawn so that it matches the general trend of the data. You should try to have as many points above the line as are below it. Do not cause the line to change slope dramatically to include only one data point that does not seem to be in line with all of the others.

A *best-fit smooth curve* should be drawn so that it matches the general trend of the data. You should try to have as many points above the line as are below it, but ensure that the curve changes smoothly. Do not cause the curve to change direction dramatically to include only one data point that does not seem to be in line with all of the others.

Definition of a Linear Relationship

A data set that is most accurately represented with a *straight line* is said to be linear. Data related by a linear relationship may be written in the form:

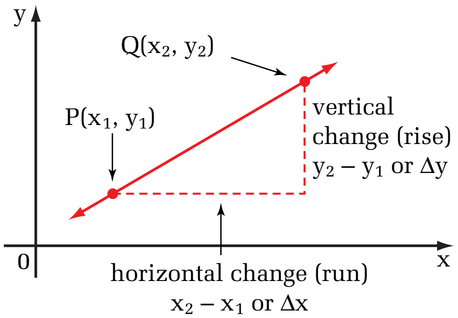
$$y = mx + b$$

Quantity	Symbol	SI unit
y value (dependent variable)	y	obtained from the vertical axis
x value (independent variable)	x	obtained from the horizontal axis
slope of the line	m	rise/run
y-intercept	b	obtained from the vertical axis when x is zero

continued ▶

Slope (m)

Calculating the slope of a line



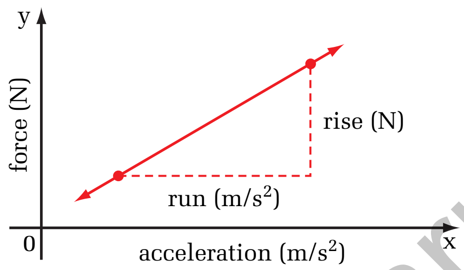
$$\text{slope}(m) = \frac{\text{vertical change (rise)}}{\text{horizontal change (run)}}$$

$$m = \Delta y/\Delta x$$

$$m = \frac{y_2 - y_1}{x_2 - x_1}, x_2 \neq x_1$$

Mathematically, slope provides a measure of the steepness of a line by dividing the vertical change (rise) by the horizontal change (run). In scientific situations, it is also very important to include units of the slope. The units will provide physical significance to the slope value.

For example:



Including the units through the calculation helps verify the physical quantity that the slope represents.

$$m = \frac{\text{rise (N)}}{\text{run (m/s}^2)} \quad \text{Recall : 1N = 1kg} \cdot \text{m/s}^2$$

$$= \frac{\text{kg} \cancel{\text{m/s}^2}}{\cancel{\text{m/s}^2}}$$

$$= \text{kg}$$

In this example, the slope of the line represents the physical quantity of mass.

Definition of a Non-linear Relationship

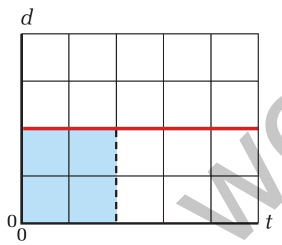
A data set that is most accurately represented with a smooth curve is said to be non-linear. Data related by a non-linear relationship may take several different forms. Two common non-linear relationships are:

(a) parabolic $y = ax^2 + k$

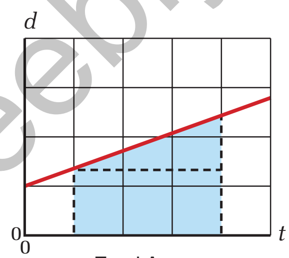
(b) inverse $y = 1/x$

Area Under a Curve

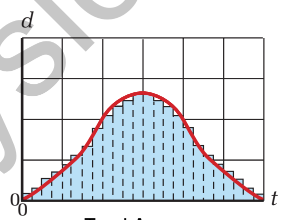
Mathematically, the area under a curve can be obtained without the use of calculus by finding the area using geometric shapes.



Total Area = Length × Width

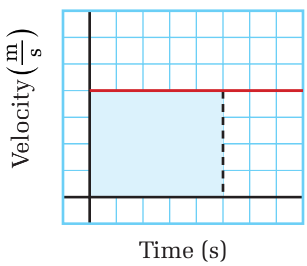


Total Area =
Area of the rectangle
+ Area of the triangle



Total Area =
Area 1 + Area 2 + Area 3 …

Always include units in area calculations. The units will provide physical significance to the area value. For example, see below:



Including the units throughout the calculation helps verify the physical quantity that the area represents.

$$\text{Area} = \Delta x \Delta y$$
$$= \text{(velocity)(time)}$$
$$= (\text{m}/\cancel{\text{s}})(\cancel{\text{s}})$$
$$= \text{m (base unit for displacement)}$$

The units verify that the area under a speed versus time curve represents displacement (m).

SET 3 Skill Review

1. (a) Plot the data in Table 1 by hand, ensuring that it fills at least two thirds of the page and has clearly labelled axes including the units.

(b) Draw a best-fit line through the plotted data.

(c) Based on the data trend and the best-fit line, which data point seems to be most in error?

(d) Interpolate the time it would take to travel 14 m.

(e) Extrapolate to find how far the object would travel in 20 s.

Table 1

Time (s)	Distance (m)	Time (s)	Distance (m)
0	2	8	17
1	4	9	20
2	7	10	23
3	8	11	24
4	5	12	26
5	12	13	29
6	16	14	28
7	16	15	33

2. (a) Plot the data in Table 2 by hand, ensuring that it fills at least two thirds of the page and has clearly labelled axes including the units.

(b) Draw a best-fit smooth curve through the plotted data.

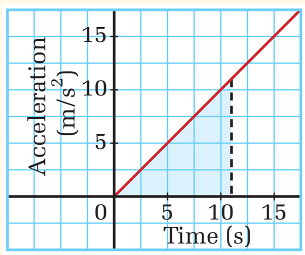
(c) Does this smooth curve represent a linear or non-linear relationship?

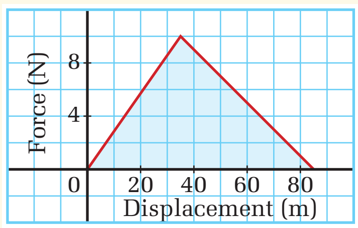
(d) At what distance is the force at the greatest value?

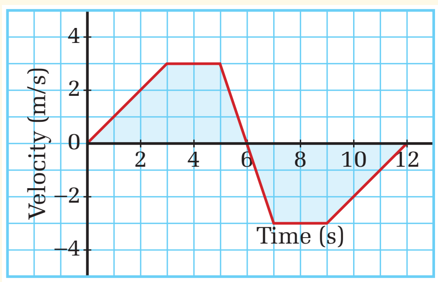
Table 2

Distance (cm)	Force (N)	Distance (cm)	Force (N)
0.0	0	2.5	1.1
0.5	0.1	2.5	1.2
0.9	0.2	2.4	1.3
1.3	0.3	2.2	1.4
1.6	0.4	2.0	1.5
1.9	0.5	1.7	1.6
2.1	0.6	1.4	1.7
2.3	0.7	1.1	1.8
2.4	0.8	0.7	1.9
2.5	0.9	0.2	2
2.6	1		

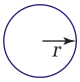
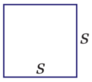
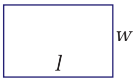
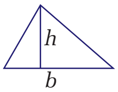
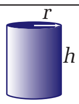
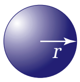
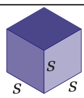
3. Find the area of the shaded region under the following graphs. Use the units to determine what physical quantity the area represents.





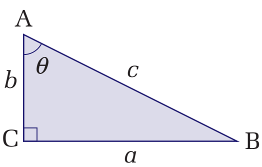


A Math Toolbox

	Perimeter/ circumference	Area	Surface area	Volume
	$C = 2\pi r$	$A = \pi r^2$		
	$P = 4s$	$A = s^2$		
	$P = 2l + 2w$	$A = lw$		
		$A = \frac{1}{2}bh$		
			$SA = 2\pi rh + 2\pi r^2$	$V = \pi r^2 h$
			$SA = 4\pi r^2$	$V = \frac{4}{3}\pi r^3$
			$SA = 6s^2$	$V = s^3$

Trigonometric Ratios

The ratios of side lengths from a right angle triangle can be used to define the basic trigonometric function sine (sin), cosine (cos), and tangent (tan).

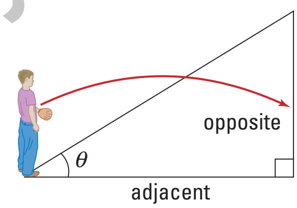


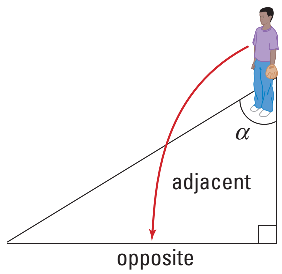
$$\sin\theta = \frac{opposite}{hypotenuse} = \frac{a}{c}$$

$$\cos\theta = \frac{adjacent}{hypotenuse} = \frac{b}{c}$$

$$\tan\theta = \frac{opposite}{adjacent} = \frac{a}{b}$$

The angle selected determines which side will be called the opposite side and the adjacent side. The hypotenuse is always the side across from the 90˚ angle. Picture yourself standing on top of the angle you select. The side that is directly across from your position is called the *opposite* side. The side that you could touch and is not the hypotenuse is the *adjacent* side.





A scientific calculator or trigonometry tables can be used to obtain an angle value from the ratio result. Your calculator performs a complex calculation (Maclaurin series summation) when the $\sin^{-1}$, or $\cos^{-1}$, or $\tan^{-1}$ operation is used to determine the angle value. Sin^{-1} is not simply a 1/sin operation.

Definition of the Pythagorean Theorem

The Pythagorean theorem is used to determine side lengths of a right angle (90°) triangle. Given a right angle triangle ABC, the Pythagorean theorem states:

$$c^2 = a^2 + b^2$$

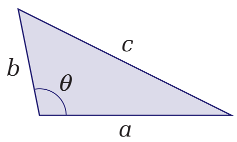
Quantity	Symbol	SI unit
hypotenuse side is opposite the 90° angle	c	m (metres)
side a	a	m (metres)
side b	b	m (metres)

Note: The hypotenuse is always the side across from the right (90°) angle. The Pythagorean theorem is a special case of a more general mathematical law called the cosine law. The cosine law works for all triangles.

Definition of the Cosine Law

The cosine law is useful when:

- determining the length of an unknown side given two side lengths and the contained angle between them;
- determining an unknown angle given all side lengths.



Angle θ is contained between sides a and b.

The cosine law states: $\boldsymbol{c^2 = a^2 + b^2 - 2ab\cos\theta}$

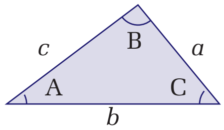
Quantity	Symbol	SI unit
unknown length side c opposite angle θ	c	m (metres)
length side a	a	m (metres)
length side b	b	m (metres)
angle θ opposite unknown side c	θ	(degrees)

Note: Applying the cosine law to a right angle triangle, setting $\theta = 90°$, yields the special case of the Pythagorean theorem.

Definition of the Sine Law

The sine law is useful when:

- two angles and any one side length are known or,
- two sides lengths and any one angle are known.



Given any triangle ABC the sine law states:

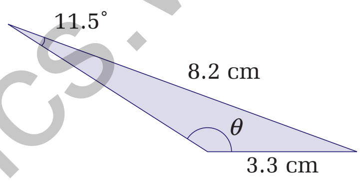
$$\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c}$$

Quantity	Symbol	SI unit
length side a opposite angle A	a	m (metres)
length side b opposite angle B	b	m (metres)
length side c opposite angle C	c	m (metres)
angle A opposite side a	A	(degrees)
angle B opposite side b	B	(degrees)
angle C opposite side c	C	(degrees)

Note: The sine law generates ambiguous results in some situations because it does not discriminate between obtuse and acute triangles. An example of the ambiguous case is shown below.

Example:

Use the sine law to solve for θ.



Sine Law: Ambiguous Case

$$\frac{\sin\theta}{8.2} = \frac{\sin 11.5°}{3.3}$$

$$\sin\theta = 0.5$$

$$\theta = 30°$$

Clearly, angle θ is much greater than 30°. In this case, the supplementary angle is required (180° – 30° = 150°). It is important to recognize, when dealing with obtuse angles (> 90°), that the supplementary angle may be required. Application of the cosine law in these situations will help reduce the potential for error.

Algebra

In some situations, it may be preferable to use algebraic manipulation of equations to solve for a specific variable before substituting numbers. Algebraic manipulation of variables follows the same rules that are used to solve equations after substituting values. In both cases, to maintain equality, whatever is done to one side must be done to the other.

continued ►

Skill Set 4 continued from previous page

Solving for "x" before Numerical Substitution

(a) $A = kx$ — x is multiplied by k, $\therefore$ divide by k to isolate x.

$\frac{A}{k} = \frac{\cancel{k}x}{\cancel{k}}$ — Divide both sides of the equation by k and

$\frac{A}{k} = x$ — simplify.

$x = \frac{A}{k}$ — Rewrite with x on the left side.

(b) $B = \frac{x}{g}$ — x is divided by g, $\therefore$ multiply by g to isolate x.

$Bg = \frac{x\cancel{g}}{\cancel{g}}$ — Multiply both sides of the equation by g and

$Bg = x$ — simplify.

$x = Bg$ — Rewrite with x on the left side.

(c) $W = x + f$ — x is added to f, $\therefore$ subtract f to isolate x.

$W - f = x + f - f$ — Subtract f on both sides of the equation and

$W - f = x$ — simplify.

$x = W - f$ — Rearrange for x.

(d) $W = \sqrt{x}$ — x is under a square root, $\therefore$ square both sides of the equation.

$W^2 = (\sqrt{x})^2$

$W^2 = x$ — Simplify.

$x = W^2$ — Rearrange for x.

Solving for "x" after Numerical Substitution

(a) $8 = 2x$ — x is multiplied by k, $\therefore$ divide by k to isolate x.

$\frac{8}{2} = \frac{\cancel{2}x}{\cancel{2}}$ — Divide both sides of the equation by 2 and

$4 = x$ — simplify.

$x = 4$ — Rewrite with x on the left side.

(b) $8 = \frac{x}{4}$ — x is divided by 4, $\therefore$ multiply by 4 to isolate x.

$(10)(4) = \frac{4x}{4}$ — Multiply both sides of the equation by 4 and

$40 = x$ — simplify.

$x = 40$ — Rewrite with x on the left side.

(c) $25 = x + 13$ — x is added to 13, $\therefore$ subtract 13 to isolate x.

$25 - 13 = x + 13 - 13$ — Subtract both sides of the equation by 13 and

$12 = x$ — simplify.

$x = 12$ — Rewrite with x on the left side

(d) $6 = \sqrt{x}$ — x is under a square root, $\therefore$ square both sides of the equation and

$6^2 = (\sqrt{x})^2$

$36 = x$ — simplify.

$x = 36$ — Rewrite with x on the left side.

Definition of the Quadratic Formula

The quadratic equation is used to solve for the roots of a quadratic function. Given a quadratic equation in the form $ax^2 + bx + c = 0$, where a, b, and c are real numbers and $a \neq 0$, the roots of it may be found using:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Statistical Analysis

In science, data are collected until a trend is observed. Three statistical tools that assist in determining if a trend is developing are *mean*, *median*, and *mode*.

Mean: The sum of the numbers divided by the number of values. It is also called the average.

Median: When a set of numbers is organized in order of size, the median is the middle number. When the data set contains an even number of values, the median is the average of the two middle numbers.

Mode: The number that occurs most often in a set of numbers. Some data sets will have more than one mode.

See examples of these on the following page.

Example #1:

Odd number of data points.

Data Set #1 12, 11, 15, 14, 11, 16, 13

$$mean = \frac{12 + 11 + 15 + 14 + 11 + 16 + 13}{7}$$

$$mean = 13$$

$$Reorganized\ data = 11, 11, 12, 13, 14, 15, 16$$

$$median = 13$$

$$\text{mode} = 11$$

Example #2:

Even number of data points.

Data Set #2 87, 95, 85, 63, 74, 76, 87, 64, 87, 64, 92, 64

$$mean = \frac{(87 + 95 + 85 + 63 + 74 + 76 + 87 + 64 + 87 + 64 + 92 + 64)}{12}$$

$$mean = 78$$

$$Reorganized\ data = 63, 64, 64, 64, 74, 76, 85, 87, 87, 87, 92, 95$$

$$median = \frac{(76 + 85)}{2}$$

$$median = 80$$

An even number of data points requires that the middle two numbers be averaged.

$$mode = 64, 87$$

In this example the data set is bi-modal (contains two modes).

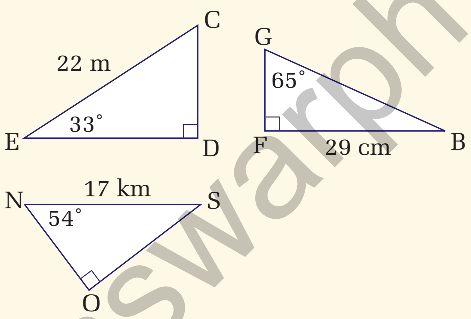
SET 4 Skill Review

1. Calculate the area of a circle with radius 6.5 m.

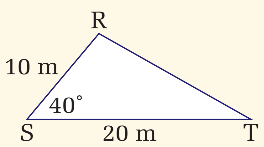
2. By how much does the surface area of the sphere increase when the radius is doubled?

3. By how much does the volume of the sphere increase when the radius is doubled?

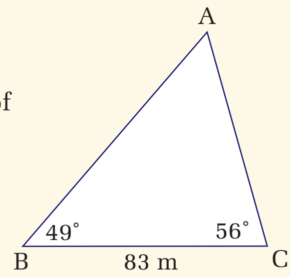
4. Find all unknown angles and side lengths.



5. Use the cosine law to solve for the unknown side.



6. Use the sine law to solve for the unknown sides.



7. Solve for x in each of the following.

(a) $42 = 7x$

(b) $30 = x/5$

(c) $12 = x \sin 30^\circ$

(d) $8 = 2x - 12^4$

8. Solve for x in each of the following.

(a) $F = kx$

(b) $G = hk + x$

(c) $a = bx \cos\theta$

(d) $b = d \cos x$

(e) $a = bc + x^2$

(f) $T = 2\pi\sqrt{\frac{1}{x}}$

9. Use the quadratic equation to find the roots of the function.
$4x^2 + 15x + 13 = 0$

10. Find the mean, median, and mode of each data set.

(a) 25, 38, 55, 58, 60, 61, 61, 65, 70, 74, 74, 74, 78, 79, 82, 85, 90

(b) 13, 14, 16, 17, 18, 20, 20, 22, 26, 30, 31, 32, 32, 35

The Metric System: Fundamental and Derived Units

Metric System Prefixes

Prefix	Symbol	Factor
tera	T	1 000 000 000 000 = 10^{12}
giga	G	1 000 000 000 = 10^{9}
mega	M	1 000 000 = 10^{6}
kilo	k	1000 = 10^{3}
hecto	h	100 = 10^{2}
deca	da	10 = 10^{1}
		1 = 10^{0}
deci	d	0.1 = 10^{-1}
centi	c	0.01 = 10^{-2}
milli	m	0.001 = 10^{-3}
micro	μ	0.000 001 = 10^{-6}
nano	n	0.000 000 001 = 10^{-9}
pico	p	0.000 000 000 001 = 10^{-12}
femto	f	0.000 000 000 000 001 = 10^{-15}
atto	a	0.000 000 000 000 000 001 = 10^{-18}

Fundamental Physical Quantities and Their SI Units

Quantity	Symbol	Unit	Symbol
length	l	metre	m
mass	m	kilogram	kg
time	t	second	s
absolute temperature	T	Kelvin	K
electric charge	Q	coulomb	C
luminous intensity	l	candela	cd

Derived Physical Quantities and Their SI Units

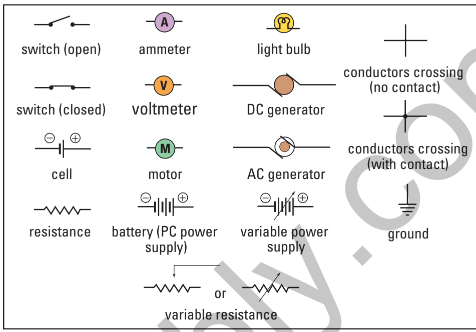
Quantity	Quantity symbol	Unit	Unit symbol	Equivalent unit(s)
area	A	square metre	m^2	
volume	V	cubic metre	m^3	
position	d	metre	m	
velocity	v	metre per second	m/s	
acceleration	a	metre per second per second	m/s^2	
force	F	newton	N	$kg \cdot m/s^2$
work	W	joule	J	$N \cdot m$, $kg \cdot m^2/s^2$
energy	E	joule	J	$N \cdot m$, $kg \cdot m^2/s^2$
power	P	watt	W	J/s, $kg \cdot m^2/s^3$
density	D	kilogram per cubic metre	kg/m^3	
pressure	p	pascal	Pa	N/m^2, kg/s^2
frequency	f	hertz	Hz	s^{-1}
period	T	second	s	
wavelength	λ	metre	m	
electric current	I	ampère (amp)	A	C/s
electric potential	V	volt	V	W/A, J/C, $kg \cdot m^2/(C \cdot s^2)$
resistance	R	ohm	Ω	V/A, $kg \cdot m^2/(C^2 \cdot s)$
magnetic field strength	B_L	tesla	T	$N \cdot s/(C \cdot m)$
temperature (Celsius)	T	degree Celsius	°C	T°C = (T + 273.15) K

Physical Constants and Data

Fundamental Physical Constants

Quantity	Symbol	Accepted value
speed of light in a vacuum	c	2.998×10^{8} m/s
gravitational constant	G	6.673×10^{-11} N · m²/kg²
Coulomb's constant	k	8.988×10^{9} N · m²/C²
charge on an electron	e	1.602×10^{-19} C
rest mass of an electron	m_e	9.109×10^{-31} kg
rest mass of a proton	m_p	1.673×10^{-27} kg
rest mass of a neutron	m_n	1.675×10^{-27} kg
atomic mass unit	u	1.661×10^{-27} kg
Planck's constant	h	6.626×10^{-34} J · s

Electric Circuit Symbols

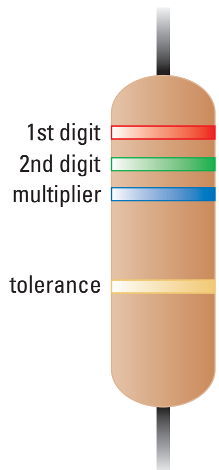


Other Physical Data

Quantity	Symbol	Accepted value
standard atmospheric pressure	P	1.013×10^{5} Pa
speed of sound in air		343 m/s (at 20°C)
water: density (4°C)		1.000×10^{3} kg/m³
latent heat of fusion		3.34×10^{5} J/kg
latent heat of vaporization		2.26×10^{6} J/kg
specific heat capacity (15°C)		4186 J/(kg°C)
kilowatt hour	E	3.6×10^{6} J
acceleration due to Earth's gravity	g	9.81 m/s² (standard value; at sea level)
mass of Earth	m_E	5.98×10^{24} kg
mean radius of Earth	r_E	6.38×10^{6} m
mean radius of Earth's orbit	R_E	1.49×10^{11} m
period of Earth's orbit	T_E	365 days or 3.16×10^{7} s
mass of Moon	m_M	7.36×10^{22} kg
mean radius of Moon	r_M	1.74×10^{6} m
mean radius of Moon's orbit	R_M	3.84×10^{8} m
period of Moon's orbit	T_M	27.3 days or 2.36×10^{6} s
mass of Sun	m_s	1.99×10^{30} kg
radius of Sun	r_s	6.69×10^{8} m

Resistor Colour Codes

Colour	Digit represented	Multiplier	Tolerance
black	0	$\times 1$	
brown	1	$\times 1.0 \times 10^{1}$	
red	2	$\times 1.0 \times 10^{2}$	
orange	3	$\times 1.0 \times 10^{3}$	
yellow	4	$\times 1.0 \times 10^{4}$	
green	5	$\times 1.0 \times 10^{5}$	
blue	6	$\times 1.0 \times 10^{6}$	
violet	7	$\times 1.0 \times 10^{7}$	
gray	8	$\times 1.0 \times 10^{8}$	
white	9	$\times 1.0 \times 10^{9}$	
gold		$\times 1.0 \times 10^{-1}$	5%
silver		$\times 1.0 \times 10^{-2}$	10%
no colour			20%



Mathematical Formulas

Formulas in Unit 1, Forces and Motion

Formula	Variables	Name, if any
$\Delta d = v\Delta t$ $v_2 = v_1 + a\Delta t$ $\Delta d = v_1\Delta t + \frac{1}{2}a\Delta t^2$ $\Delta d = v_2\Delta t - \frac{1}{2}a\Delta t^2$ $v_2^2 = v_1^2 + 2a\Delta d$	Δd = displacement v = velocity v_1 = initial velocity v_2 = final velocity a = acceleration Δt = time interval	motion formula
$F_g = mg$	F_g = force of gravity m = mass g = acceleration due to gravity (on Earth)	weight
$F_f = \mu_s f_N$ $F_f = \mu_k f_N$	F_f = force of friction μ_s = coeffcient of static friction μ_k = coeffcient of kinetic friction F_N = normal force	friction
$F_{Net} = ma$ $W = F_{\parallel}\Delta d$	F_{Net} = net force a = acceleration	Newton's second law

Formulas in Unit 2, Energy, Work, and Power

Formula	Variables	Name, if any
$W = F_{\parallel}\Delta d$ $W = \lvert F\rvert \Delta d \cos\theta$	W = work done $F_{\parallel}$ = force parallel to Δd $\lvert F\rvert$ = magnitude of applied force Δd = displacement θ = angle of degrees	work done
$E_k = \frac{1}{2}mv^2$	E_k = mechanical kinetic energy m = mass v = velocity	mechanical potential energy
$E_g = mg\Delta h$	E_g = gravitational potential energy m = mass g = acceleration due to gravity (on Earth) Δh = change in height	gravitational potential energy
$E_T = E_g + E_k$	E_T = total mechanical E_g = mechanical gravitaional potential energy E_k = mechanical kinetic energy	conservation of mechanical energy
$W_{nc} = E_{final} - E_{initial}$	W_{nc} = work done by non-conservative forces E_{final} = final energy $E_{initial}$ = initial energy	work done by non-conservative forces
$\Delta E = W + Q$	ΔE = change in energy W = work done Q = heat	first law of thermodynamics
$T = T_c + 273.15$	T_c represents Celsius	Kelvin/Celsius temperature conversion

$Q = mc\Delta T$ $Q = mL_f$ $Q = mL_v$	Q = heat m = mass c = specific heat capacity ΔT = change in temperature L_f = latent heat of fusion L_v = latent hat of vaporization	heat heat of fusion heat of vaporization
$P = W/\Delta t$ $P = E/\Delta t$	P = power W = work done E = energy transferred	power
Efficiency = $E_o/E_i \times 100\%$ Efficiency = $W_o/W_i \times 100\%$	E_o = energy output E_i = energy input W_o = work output W_i = work input	efficiency

Formulas in Unit 3, Waves and Sounds

$T - \Delta t/N$ $f = N/\Delta t$ $f = 1/T$	N = number of oscillations Δt = time intervals T = period of oscillations f = frequency of oscillations	period frequency frequency
$v = f\lambda$	v = velocity of a wave f = frequency of a wave λ = wavelength	wave equation
open *resonance* $= \frac{n}{2}\lambda$ closed *resonance* $= \left(n - \frac{1}{2}\right)\frac{\lambda}{2}$	n = number of wavelengths λ = wavelength	open tube resonance closed tube resonance
Beat frequency = $\lvert f_1 - f_2 \rvert$	f_1 = frequency of 1st source f_2 = frequency of 2nd source	beat frequency
$v_s = 0.59T + 331$	v_s = speed of sound in air T = air temperature in °C	speed of sound in air
Mach number = v_{object}/v_{sound}	v_{object} = speed of object v_{sound} = speed of sound	Mach number

Formulas in Unit 4, Light and Geometric Optics

$f = R/2$	f = mirror focal length R = radius of curvature	focal length of a curved mirror
$n = c/v$ $n = \sin\theta_i / \sin\theta_R$ $n_1 \sin\theta_1 = n_2 \sin\theta_2$	n = index of refraction c = speed of light in a vacuum v = speed of light in medium θ_i = angle of incidence θ_R = angle of refraction n_1 = index of refraction 1st medium θ_1 = angle of incidence n_2 = index of refraction 2nd medium θ_2 = angle of refraction	refractive index Snell's law (general form)
$\sin\theta_c = 1/n$	θ_c = critical angle n = index of refraction	critical angle

continued ▶

Appendix C continued from previous page

$d_{apparent} = d_{actual}\ (n_2/n_1)$	$d_{apparent}$ = apparent depth d_{actual} = actual depth n_1 = index of refraction 1st medium n_2 = index of refraction 2nd medium	apparent depth
$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$	f = lens' focal length n = index of refraction R_1 = radius of curvature of one side of lens' surface R_2 = radius of curvature of the other side of the lens' surface	lens-maker's formula
$M = h_i/h_o = -d_i/d_o$	M = magnification h_i = height of the image h_o = height of the object d_i = image distance d_o = object distance	magnification of a lens and a curved mirror
$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$	f = lens' focal length d_o = object distance d_i = image distance	thin lens and curved mirror equation
Formulas in Unit 5, Electricity and Magnetism		
$Q = Ne$	Q = amount of charge N = number of electrons (excess or deficit) e = electron charge	amount of charge
$V = \Delta E_Q/Q$ $V = IR$	V = potential difference (voltage) ΔE_Q = energy transfer Q = amount of charge I = electric current R = resistance	potential difference
$I = Q/\Delta t$	I = current Q = amount of charge Δt = time ihnterval	current
$R = r\frac{L}{A}$	R = resistance r = resistivity L = length of conductor A = cross-sectional area	resistance
$R_s = R_1 + R_2 + R_3 + \ldots + R_N$ $1/R_p = 1/R_1 + 1/R_2 + 1/R_3 + \ldots + 1/R_N$	R_s = total series resistance R_p = total parallel resistance R_1, R_2, R_3, R_N = individual resistors	series and parallel resistance
$Vs = \mathcal{E} - V_{int}$	V_s = terminal voltage $\mathcal{E}$ = electromotive force V_{int} = internal potential drop	terminal voltage
$P = VI$ $P = I^2 R$ $P = V^2/R$	P = electric power I = electric current V = electric potential R = electric resistance	electric power

$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$	V_1 = potential 1st side V_2 = potential 2nd side N_1 = number of turns 1st side N_2 = number of turns 2nd side I_1 = current 1st side I_2 = current 2nd side	transformer
$B_L = F/IL$	B_L = magnetic field strength F = force I = current L = length of conductor	magnetic field strength
$L = n\ell$	L = length of conductor n = number of turns ℓ = length of one turn	conductor length

Appendix D

Safety Symbols

The following safety symbols are used in this Physics 11 textbook to alert you to possible dangers. Make sure that you understand each symbol in a lab or investigation before you begin.

	Thermal Safety This symbol appears as a reminder to be careful when handling hot objects.
	Sharp Object Safety This symbol appears when there is danger of cuts or punctures caused by the use of sharp objects.
	Fume Safety This symbol appears when chemicals or chemical reactions could cause dangerous fumes.
	Electrical Safety This symbol appears as a reminder to be careful when using electrical equipment.
	Skin Protection Safety This symbol appears when the use of caustic chemicals might irritate the skin or when contact with micro-organisms might transmit infection.
	Clothing Protection Safety A lab apron should be worn when this symbol appears.
	Fire Safety This symbol appears as a reminder to be careful around open flames.
	Eye Safety This symbol appears when there is danger to the eyes and safety glasses should be worn.
	Chemical Safety This symbol appears when chemicals could cause burns or are poisonous if absorbed through the skin.

Safety symbols used in the textbook

Look carefully at the WHMIS (Workplace Hazardous Materials Information System) safety symbols shown below. These symbols are used throughout Canada to identify dangerous materials in all work-places, including schools. Make sure that you understand what these symbols mean. When you see these symbols on containers in your classroom, at home, or in a workplace, use safety precautions.

Compressed Gas	Flammable and Combustible Material
Oxidizing Material	Corrosive Material
Poisonous and Infectious Material Causing Immediate and Serious Toxic Effects	Poisonous and Infectious Material Causing Other Toxic Effects
Biohazardous Infectious Material	Dangerously Reactive Material

WHMIS symbols

Chapter Review and Unit Review Numerical Problems

Chapter 1

16. 2.6%

17. (a) 0.3%
(b) Yes. The experimental measurements are very close to the theoretical value so such a small percent deviation is reasonable.

18. (a) 11.5 Hz
(b) 11 Hz
(c) 11 Hz

Unit 1

Chapter 2

15. (a) with respect to the ground
(b) with respect to the truck

17. (a) 17 km **(b)** 7.0 km[S]
(c) 7.0 km[N]

18. 26 km[W]

19. (a) 0.40 km downstream
(b) 0.53 km/h downstream

20. 4.35 years

21. (a) 11.4 km from Vectorville
(b) 0.571 h or 34.2 min

22. (a) uniform
(b) non-uniform
(c) non-uniform
(d) non-uniform
(e) uniform

24. -2.8 m/s^2

25. 3 m/s

26. -1.9 m/s

28. (a) 16.7 m/s **(b)** 2.8 m/s^2

29. (a) 27 m **(b)** 8.0 m/s

30. (a) -1.2 m/s^2 **(b)** 6.9 s

31. 18 m [down]

32. (a) 23 s **(b)** 550 m

Chapter 3

11. Displacement is the same; distance flown and time of travel are different. Pilots may want to fly along a component to partially avoid a headwind or to take advantage of a tailwind.

12. 9.40 km[N], -9.40 km[S], -3.42 km[E], 3.42 km[W]

13. (a) 71 km/h[SW]
(b) 3.9 m/s^2[SW] or 5.1×10^4 km/h^2[SW]

14. (b) 3.6 km[S34°W]

15. (a) 6.6 km[N31°W]
(b) 4.4 km/h[N31°W]

16. (b) 7.9 m/s[NW]

17. (a) 18 km[W24°S]
(b) 14 km/h[W24°S]

18. (a) 1.3 m/s[N]
(b) 3.7 m/s[S]

19. (a) [E26°N]
(b) 1.7 m/s[E]
(c) 47 min

20. (a) 8.4 m[E] and 18 m[N]
(b) 28 km[E] and 39 km[S]
(c) 12 m/s[W] and 8.6 m/s[S]
(d) 12 m/s^2[W] and 21 m/s^2[N]

21. 4.4 m/s[N5.4°E]

22. 12 km[W24°N]

23. (a) 2.0×10^1 km[N16°E]
(b) 9.9 km/h[N16°E]

24. 0.217 m/s^2[S19.7°W]

25. (a) 300 km/h[N]
(b) 1 h
(c) 0.6 h
(d) No

26. (a) He should aim upstream at an angle 41° with respect to the river bank.
(b) 2.3 min

Chapter 4

22. (a) 4.4×10^3 N
(b) 1.5×10^3 N
(c) 0.25

24. (a) 300 N **(b)** 0.8 m/s^2

25. 4 s

26. (a) -1.1 m/s^2 **(b)** 0.12

27. $T_h = 4.1 \times 10^2$ N, $T_v = 4.6 \times 10^2$ N

28. 0.4 m/s^2

29. (a) 3.8×10^2 N
(b) 0.18 m/s^2

30. 50 N[E70°N]

31. (a) 0.80 m/s^2 **(b)** 16 N

Unit 1 Review

33. 13 km[E13°S]

34. 64 km/h[E51°S]

35. (a) 0.50 h
(b) 55 km[S]
(c) 110 km/h[S]

36. (i) B **(ii)** C **(iii)** A **(iv)** D

37. (a) 0.4 km **(b)** 6 min
(c) 1 km

38. 2.5 m/s^2[N]

39. 5.0×10^1 m

40. 9.0 s

41. 20 s

42. (i) A **(ii)** C **(iii)** E

43. (a) 5.1 km[S28°E]
(b) 1.7 m/s[S28°E]

44. 1.8 m/s[N19°E]; 8.8×10^2 s; 5.3×10^2 m downstream

45. (a) 7.4 m/s[N]
(b) 9.5 m/s[N]
(c) 5.3 m/s[N]

46. 59 km/h[E17°S]

47. 45 km/h[E45°S]

48. Heading[N23.5°W]; 201 m/s[N30.0°W]

49. 1.9×10^4 m/s^2[N]

50. 6.8 m/s^2[NW]

51. 3.9 m/s[NE]

52. (b) It would accelerate in the horizontal direction.
(c) It would have constant velocity.
(d) It would slow down and stop.

53. (a) 2.7×10^2 N[W]
(b) 4.0 m/s^2[E]
(c) 5.0×10^1 m

54. (a) 0.30 m/s^2[N]
(b) 8.1 N[N]
(c) 12 N [at an angle of 25°]

55. 15 N[E19°S]

56. 1.2×10^2 N[up]

Unit 2

Chapter 5

14. Air resistance slows down rain drops.

15. (a) Ground pushes up, gravity pulls down, engine propels car forward, ground resists backward.
(b) The forward force (from the car's engine) does work.

16. 44 N

17. 3.50×10^2 J

18. 228 N

19. 1.44×10^4 J

20. 6.2×10^2 J

21. 438 J

22. 5.0 m: 1.0×10^2 J, 13 m/s; 15.0 m: 5.8×10^2 J, 31 m/s; 25.0 m: 8.1×10^2 J, 36 m/s

23. 73°
24. the 55 kg athlete
25. (a) 3.2 m/s; 3.4×10^2 J
 (b) 1.2 m
26. 5.0×10^1 kg
27. 17 J; 4.2 m/s
28. 11.1 m/s
29. 30 m/s

Chapter 6

32. 1.2×10^5 J
33. 7.9°C
34. 5.1×10^3 J
35. 273.15 K; 100°C; 293.15 K
36. 6×10^4 J, 1×10^5 J
37. 1.4×10^6 J
38. 3.5×10^2 W
39. (a) 2.7×10^5 J (c) 4×10^6 J
 (b) 2×10^6 J (d) 4.5×10^9 J
40. (b) a = 1.0 m/s^2
 (c) 4.6 m
 (d) 57 J
 (e) 19 W
41. 100% to 15% to 9% to 7.6%
42. 5×10^3 W
43. 2 m

Unit 2 Review

50. (a) 8×10^2 N (b) 1.5×10^3 J
51. 16.8 m/s
52. 49 kg
53. 1.8×10^3 J
54. 31 m/s, 22 m/s, 18 m/s
55. (a) 6.17×10^2 km/h
 (b) 99.9%
56. (a) -5.8×10^3 J
 (b) 3.6 (c) yes, $\mu > 1$
57. (a) 6.1×10^3 N
 (b) 1.8×10^7 J
58. 0.543 kg
59. 1.8 h

Unit 3

Chapter 7

21. 0.25 Hz
22. the wavelength doubles
23. 0.4 m
24. 1.67×10^{-2} Hz; 5.72 m
25. (a) 1.4 Hz (b) 3.7 cm/s
26. 1.6 Hz
27. 680 km
28. (a) 1.2 Hz (b) 0.84 s
29. (a) 1.02 s (b) 2.56%
 (c) 225 h or 9.38 days
 (d) shorten the pendulum

Chapter 8

28. (a) 307 m/s (c) 343 m/s
 (b) 3.3×10^2 m/s (d) 352 m/s
29. (a) 40.7°C (c) 3.39°C
 (b) 22.0°C (d) –22.0°C
30. 4.0°C
31. 7.0×10^2 m
32. (a) periodic increase and decrease of volume
 (b) 3 Hz
33. (a) 436.5 Hz or 443.5 Hz
 (b) If, as the string is tightened, the beat frequency increases, then the guitar was at 443.5 Hz, while if the beat frequency decreases, then the guitar was at 436.6 Hz.
34. (a) The human brain responds to harmonies, i.e. simple fraction ratios of pitch.
35. (a) Increases in pitch at specific, well-defined tube lengths.
 (b) $L_1 = 0.098$ m, $L_2 = 0.29$ m, $L_3 = 0.49$ m, $L_4 = 0.68$ m
36. (a) 0.38 m (b) 9.0×10^2 Hz

Chapter 9

31. The well is less then 176 m deep.
32. The vehicle is approaching.
33. (a) 0.082 m (b) 0.073 m
34. 0.062 m
35. 2.8×10^3 km/h
36. 1.32
37. 1.30×10^3 m
38. 1.3×10^2 m
39. 7 m
40. 83 Hz, 55 Hz, 110 Hz
41. Yes, with 0.03 s to spare.

Unit 3 Review

49. 3.0 m/s
50. 0.167 Hz
51. 0.8 m
52. 7.14×10^9 Hz
53. 0.73 m
54. 312 Hz
55. 0.69 m
56. 0.259 m
57. 382.8 Hz or 385.2 Hz
58. 2.16×10^3 m
59. (a) 1.6 (b) It will increase.
60. 0.02 m to 20 m
61. 2.4 s
62. 3.3 s
63. 7.55×10^4 Hz
64. 2.00 m
65. The resonance frequencies are in the range of 100 to 200 Hz, so a low voice would be more likely to appreciate resonance.
66. –8°C

Unit 4

Chapter 10

20. 4.6 m
21. (a) 55° (b) 110°
22. 66°
23. 56°
24. 16°
25. 6.25 m
26. 7.0 m/s
27. 3.5 m/s
29. 52 cm
30. –30 cm
31. 0.850 m
32. $d_i = d_o = R$; $h_o = -h_i$; M = –1
33. The image is real and inverted; $d_i = 0.75$ m, $h_i = -1.2$ cm
34. The image is real and inverted; $d_i = 1.2 \times 10^2$ cm, $h_i = -7.0$ cm
35. The image is virtual and upright; $d_i = -2.4$ m, $h_i = 6.0$ cm
36. The image is virtual and upright; $d_i = -0.7$ m, $h_i = 0.1$ m
37. The image is virtual and upright; $d_i = -0.39$ m, $h_i = 12$ cm
38. 17 cm

Chapter 11

20. 1.95
21. 22.8°
22. The ray exits at 30°, 5.7 cm from the bottom corner (assuming it entered 3.5 cm from the same corner).
23. 2.6×10^{-9} s
24. (a) 1.2 (b) 19° (c) 39°
25. 22°
26. 390 nm

28. 1.9 m

29. 68°

30. ± 4 cm

Chapter 12

27. 1.50; crown glass

28. 23.1 cm

29. $h_i = -13$ cm; $d_i = 42$ cm; the image is real, inverted and smaller than the object.

30. $h_i = 5.00$ cm; $d_i = -10.0$ cm; the image is virtual, upright and smaller than the object.

31. The lens is convex; the object is within the focal point.

32. $h_i = -4.0$ cm; $d_i = 19$ cm

33. $h_i = 1.1$ cm; $d_i = -5.1$ cm

34. $h_i = 4$ cm; $d_i = -10$ cm

35. 56 cm

36. 250

37. $f_{obj} = 0.441$ cm, $f_{eye} = 2.50$ cm

38. (a) 14.4 cm (b) 10.3 cm

39. (a) 0.80 (b) 2.5

40. f = 0.185 m; $d_o = 0.188$ m

Unit 4 Review

49. (a) $d_i = -f$, $M = 2$; the image is virtual, upright and larger.
 (b) $d_i = 2.33$ f, $M = -1.3$; the image is real, inverted and larger
 (c) $d_i = 1.5$ f, $M = -0.50$; the image is real, inverted and smaller

50. 48°

51. 12°

52. (a) 2.4 m/s (b) 1.2 m/s

53. 7.0×10^1 m

54. –0.90 m

55. (a) $d_i = -36.0$ cm, $h_i = 6.00$ cm; the image is virtual, upright and larger
 (b) $d_i = 72.0$ cm, $h_i = -6.00$ cm; the image is real, inverted and larger
 (c) $d_i = -32.7$ cm, $h_i = 6.00$ cm; the image is virtual, upright and larger

56. (a) $d_i = -7.50$ cm, $h_i = 1.25$ cm; the image is virtual, upright and smaller
 (b) $d_i = -12.0$ cm, $h_i = 0.800$ cm; the image is virtual, upright and smaller
 (c) $d_i = -14.3$ cm, $h_i = 0.571$ cm; the image is virtual, upright and smaller

57. $d_i = 24.0$ cm, $M = 0.600$

58. $d_i = -45.0$ cm, $M = 0.100$; the image virtual, upright and smaller

59. 1.60×10^8 m/s

60. 1.6×10^{-9} s

61. 1.4

62. 25°

63. 33°

64. 350 nm

65. 15°

66. 4.1 m

67. 1.4

68. 60°

69. 38.6°

70. (a) 1.99×10^8 m/s
 (b) 1.96×10^8 m/s

71. -1.50; the image is real, inverted and larger

72. $h_o = 80.0$ cm, $d_o = 1.40$ m

Unit 5

Chapter 13

24. 3×10^3 Ω

25. (a) 12 A (b) 2.5×10^3 C
 (c) 3.0×10^5 J

26. 5.0×10^5 J

27. 1.77 cents

28. 37.5 Ω

29. $I_1 = 6.0$ A, $V_1 = 150$ V, $I_2 = 1.0$ A, $V_2 = 3.0 \times 10^1$ V, $I_3 = 5.0$ A, $V_3 = 3.0 \times 10^1$ V

30. 9.93 s

31. (a) 1.9 Ω (b) 1.4×10^2 Ω
 (c) 0.82 A (d) 98 W

32. 24.3 V, 0.517 Ω

Chapter 14

27. The magnetic field would be 5 times stronger.

28. 2.03×10^{-4} km/h

29. (a) 22.0° E (b) 112° E

30. (a) 2 times increase
 (b) 9 times increase
 (c) 2 times increase

Chapter 15

19. 0.025

20. (a) 25.0 A (d) 1.46×10^3 W
 (b) 9.60×10^2 V A (e) 1.52 A
 (c) 1.56 A

21. (a) 5.12×10^4 W
 (b) 4.90×10^4 W
 (c) 300 turns
 (d) 2.20×10^3 W
 (e) 7.66 A

Unit 5 Review

38. 1.2 A[into the page]

39. 2.0 min

40. (a) 14 N[up] (b) 0

42. Series: 4.00 Ω: 1.2 A, 5.0 V; 5.00 Ω: 1.2 A, 6.2 V.
 Parallel: 5.00 Ω, 3.8 V; 7.50 Ω : 0.50 A, 3.8 V

43. (a) 5.0×10^1 V (c) 12 Ω
 (b) 1.0×10^2 V (d) 2.7 A

44. (a) 17 V (b) 6.5 Ω
 (c) 14 V

A

absorption coefficient for sound, a property of each material that indicates the degree to which that material absorbs sound energy (9.3)

absolute zero the temperature at which the particles of a substance have zero kinetic energy, determined to be –273.15 ˚C (6.1)

AC generator an instrument that converts mechanical energy into electrical energy and produces alternating current (current that oscillates back and forth) (15.1)

acceleration the rate of change of velocity of an object (2.4)

acceleration due to gravity the acceleration of an object towards the centre of a celestial body when the gravitational attraction of the mass of the body is the only force acting on the object (4.2)

accommodation adjustment of the eye's lens by muscles in the eye in order to focus an image on the retina (12.3)

accuracy the degree to which the results of an experiment or calculation approximate the true value (Skill Set 1)

acoustical design plans for a room or building that will create desired sound characteristics (9.4)

acoustical properties the characteristics of a room or building that determine how sound is reflected in the room (9.4)

acoustical shadows regions of destructive interference of or physical barriers to sounds in an auditorium (9.4)

action-at-a-distance a force that two bodies exert on each other even though the bodies are not in contact (12.2)

alternator converts alternating current from an AC generator into direct current by the use of specially designed electric circuitry (15.1)

ammeter a device that measures the current in an electric circuit (13.2)

ampere the unit of electric current equivalent to one coulomb of charge passing a point in a circuit in one second (13.2)

amplitude the distance from the rest position to the maximum displacement for an object in periodic motion; or, for a wave, the distance from the rest position to the maximum point of the crest or minimum point of the trough (7.1, 7.2)

angle of deviation the angle between the direction of a ray incident on a prism and the direction of the emergent ray after having refracted at two surfaces of the prism (11.3)

angle of incidence the angle between the normal to a surface and the ray representing the incoming wave or light (7.4)

angle of reflection angle between the normal and the ray reflected from a surface, such as a mirror (7.4, 10.1)

angle of refraction angle that the refracted light ray or wave makes with the normal to the surface or boundary (11.2)

anode the electrode that accepts electrons; in a voltaic cell, the negative electrode; in an electrolytic cell, the positive electrode (13.1)

antinodal line a stationary line of points caused by constructive interference of individual waves (7.4)

antinode positions of maximum amplitude of a standing wave caused by the constructive interference of two individual waves travelling in opposite directions (7.3)

aperture part of an optical instrument through which electrons, light, or radio waves can pass (12.3)

apparent depth an effect observed in water in which the image of an object appears closer to the surface than the object; depends on the relative indices of refraction of air and water (11.3)

armature in a motor or generator, the coil with an iron core that rotates in a magnetic field (same as rotor) (14.4)

articulators any of the mouth and nasal cavity, the tongue and the lips, which modify specific sounds for speech and singing (9.1)

astigmatism the shape of the cornea in an eye is not spherical, causing vertical or horizontal lines to focus incorrectly (12.3)

attitude of an image formed by a mirror or lens, its orientation, upright or inverted (10.0)

audible sound frequencies in the range 20 to 20 000 hertz (Hz) (8.2)

auditory canal the part of the outer ear into which sound is funneled (9.1)

auditory nerve a nerve connecting the inner ear to the brain, along which signals are carried (9.1)

average acceleration rate of change of velocity depending only on initial and final values (2.4)

average velocity the quotient of the displacement and the time interval depending only on initial and final values (2.2)

B

back emf a potential difference generated by the motion of the current carrying coil in a motor, moving in the magnetic field, that opposes the potential difference that is driving the motor (15.2)

battery a combination of two or more voltaic cells that can convert chemical energy into electrical energy (13.1)

beat frequency frequency of envelope wave produced by the superposition of two waves of similar but not identical frequencies (8.3)

beats periodic variations in amplitude of a wave caused by superimposing two waves of nearly the same frequency (8.3)

bel a unit of sound intensity level; 1 bel = 10 pW/m^2 (8.2)

biconvex a lens in which both surfaces are convex, or curving outwards; also called double convex (12.1)

Big Bang a theoretical event considered to be the beginning of the universe (4.5)

Big Crunch a possible final event for the universe in which all matter and radiation recollapse into a point (4.5)

biogas gas created by the decay of rotting plant-matter; composed of methane, carbon dioxide and hydrogen sulphide gas (6.3)

blend the mixture of sounds created by the performers that is heard by the audience; in concert halls with good blends, no single instrument dominates (9.4)

brilliance an acoustical property of a room obtained when the reverberation time for high frequencies is longer than for low frequencies; opposite to warmth (9.4)

C

cathode the electrode that is the source of electrons; in a voltaic cell, positive; in an electrolytic cell, negative (13.1)

centre of curvature the centre of a sphere that would be formed if a spherical curved surface were extended into a sphere (10.3)

chromatic aberration an optical lens defect in which light of different wavelengths is focussed at different locations, causing colour fringes; due to the different index of refraction of different wavelengths (colours) of light (12.2)

circuit elements parts of a circuit, such as the loads and power supply (13.2)

clarity an acoustical property of a room characterized by a low intensity of reflected sound compared to the direct sound; opposite to fullness (9.4)

classical mechanics the study of forces and the resulting motion of macroscopic objects with velocities much less than the speed of light (4.3)

closed air column an air column that is closed at one end and open at the other (8.4)

closed circuit a complete circuit, in which current is able to flow (13.2)

cochlea the snail-shaped canal in the inner ear consisting of three fluid filled canals separated by membranes; one of the membranes (basilar membrane) contains thousands of tiny hair cells having their extensions (hairs) that are receptor cells for sound waves (9.1)

coefficient of friction for two specific materials in contact, the ratio of frictional force to the normal force between two surfaces (4.2)

commutator a device which passes current to or from the rotor (or armature) in an electric motor or generator (14.4)

complex circuit a circuit consisting of loads in a combination of parallel and series connections (13.4)

component of a vector part of a vector that is parallel to one of the axes of the coordinate system (3.3)

component wave a wave that combines with another wave to produce a resultant wave (7.3)

compression a region of higher pressure compared to the surrounding medium; longitudinal waves have both compressions and rarefactions (8.1)

concave mirror a mirror shaped similar to the inner surface of a segment of a sphere (10.3)

concave lens a lens that is thinner in the middle than at the ends; it causes rays to diverge when they pass through it (12.2)

concavo-convex lens a converging lens that has one concave and one convex surface (12.1)

conclusion an interpretation of the results of an experiment that relate to the hypothesis being tested (1.1)

conductor a material, like a metal, that allows electric charges to flow easily (13.1)

conservation of mechanical energy processes in which the total mechanical energy (kinetic and gravitational potential energy) is conserved (5.4)

conservative force a force that does work on an object in such a way that the amount of work done is independent of the path taken (5.4)

consonance combinations of musical notes that sound pleasant together (9.3)

constant acceleration acceleration that is not changing over a certain interval of time (2.4)

constant velocity the velocity that is unchanging in a given time interval (2.3)

constructive interference resultant wave has a larger amplitude than its component waves (7.3)

contact forces the force exerted by objects that are touching each other (4.2)

control a sample group to which experimental results can be compared (1.1)

converge to come together at a common point (10.2)

coordinate system a frame of reference consisting of perpendicular axes (3.1)

converging rays light rays that come together at the focal point after reflection or refraction from a mirror or lens (10.2)

convex mirror a mirror shaped similar to the outer surface of a segment of a sphere (10.3)

convex lens a lens which causes a parallel set of light rays that strike it to converge on a single point on the opposite side of the lens (12.1)

convex meniscus a lens that is thicker in the middle than at the edges and has one concave surface and one convex surface (12.1)

convexo-concave a lens that is thinner in the middle than at the edges and has one convex and one concave surface; also called concave meniscus (12.1)

coulomb amount of charge that passes a point in a circuit that is carrying a current of one ampere (13.1, 13.2)

crest the highest point on a wave (7.2)

critical angle the angle of incidence that produces a refracted light ray at an angle of 90° from the normal (11.4)

Curie point the temperature above which a magnet, when heated, loses its permanent magnetism and is destroyed (14.1)

current the net movement of electric charges (13.2)

cycle one complete repeat of a pattern of periodic motion, such as the crest of a wave to the next crest (7.1)

D

DC generator a device that converts mechanical energy into electrical energy and produces a direct current (15.1)

decibel the most common unit to describe sound intensity level; 1 decibel = 0.1 bel (8.2)

dependent variable the quantity that may change or respond because of changes in the independent variable (1.1)

destructive interference the situation when a combined or resultant wave has a smaller amplitude than at least one of its component waves (7.3)

deviation the change in direction of light after passing through a prism (11.3)

diamagnetic describes materials that become weakly magnetized in the opposite direction of an applied field (14.2)

diffraction the bending of waves around a barrier (7.4)

diffuse reflection the reflection in which the reflected light rays are not parallel to one another, as they are from a rough surface (10.1)

dipping needle a needle, freely suspended at its centre of gravity, used to measure the direction of the Earth's magnetic dip (14.1)

dispersion the separation of visible light into its range of colours (11.5)

displacement the change in the position of an object; the difference of the final and initial positions (2.2)

displacement antinode in a standing sound wave, the positions of maximum displacement of the particles (8.4)

displacement node in a standing sound wave, the positions of minimum displacement of the particles (8.4)

dissonance combinations of musical notes that sound unpleasant when played together (9.3)

diverge to spread out from a common point (10.2)

diverging lens a lens that is thinner in the middle than at the ends; it causes rays to diverge when they pass through it; also called concave lens (12.2)

domain small region in iron containing material in which individual "magnets" on the atomic level, are all aligned in the same direction (14.1)

Doppler effect change in the observed frequency (or wavelength) of a sound due to motion of the source or the observer (9.2)

double concave a diverging lens that has two concave surfaces (12.2)

dynamics the study of the motions of bodies while considering their masses and the responsible forces; simply, the study of *why* objects move the way they do (4.1)

E

eardrum a thin layer of skin stretched completely across the interior end of the auditory canal that vibrates in response to sound waves (9.1)

echo reflected sound (9.4)

echolocation determining position of obstacles and prey by emitting sound pulses and detecting time interval for sound to be reflected (9.2)

eddy currents electric currents induced within the body of a conductor when that conductor is subjected to a changing magnetic field (15.2)

efficiency the ratio of useful energy or work to the total energy or work input; describes how well a machine or device converts input energy or work into output energy or work (6.2)

electric current the movement of electric charge (13.2)

electric generator a device that converts mechanical energy into electric energy (15.3)

electric potential difference the difference in electric potential energy per unit charge between two points (13.0)

electric potential energy the energy possessed by electric charges due to their interaction with each other (13.1)

electric resistance inhibits the flow of electric current in a circuit (13.3)

electrode an electric conductor through which a current enters or leaves an electric device, such as a voltaic cell (13.1)

electrolyte a solution that can conduct electric current (13.1)

electromagnet a magnet created by placing an iron core inside a solenoid (14.3)

electromagnetic force the fundamental force which operates between charged particles; has an infinite range (4.5)

electromagnetic induction the generation of a current due to the relative motion of a conductor and a magnetic field (15.1)

electromagnetic wave wave consisting of changing electric and magnetic field (7.2)

electromagnetism phenomena associated with moving electric charges and magnetic fields (14.3)

electromotive force (*emf*) the potential difference produced by electromagnetic induction or by chemical reactions in a battery, that exists between the terminals when no current is flowing (15.1)

electron flow the net movement of negative charge (13.2)

electrostatics the study of electrical charges at rest (13.1)

elementary charge the quantity of charge on an electron or proton, equivalent to $e = 1.60 \times 10^{-19}$ C (13.2)

energy the ability to do work (6.3)

ensemble the ability of members of a performing group to hear each other play during a performance (9.3)

equations of motion set of mathematical equations describing the motion of an object undergoing uniform acceleration that relate velocity, displacement, acceleration, and time (2.5)

equilibrium the state of an object when the forces acting on it are in balance (4.4)

equivalent resistance the calculated total effective resistance of a group of resistors combined either in series or parallel or both (13.4)

error analysis the process of estimating the errors in measurements (Skill Set 1)

estimated uncertainty error in a measurement due to the natural limitations of the measuring device; usually described as half of the smallest division of the measuring device (Skill Set 1)

Eustachian tube a tube composed of bone and cartilage that drains fluid from the middle ear and allows air in or out to maintain the atmospheric pressure balance (9.1)

exchange particle an elementary particle thought to be responsible for the action of a fundamental forces (4.5)

experiment the test of a hypothesis under controlled conditions (1.1)

eyepiece the lens in an optical device that is used to observe the image created by the objective lens (12.0)

F

fair test an investigation in which the desired variables are adequately and objectively tested; if an investigation is a fair test, repeating it will produce similar results (1.1)

ferromagnetic a material whose atoms or molecules are magnets and tend to group into domains (14.2)

field theory a theory in which a field, rather than a magnet, electric charge, or gravitational mass, is the source of the force (14.3)

first law of thermodynamics energy cannot be created or destroyed; the energy of a closed system is conserved (6.1)

fluctuating magnetic fields magnetic fields that change in strength (15.3)

focal length the distance from the focal point to the vertex of the mirror or lens (10.3, 12.1)

focal point a point on the principal axis of a mirror or lens at which parallel light rays meet after being reflected or refracted (10.3, 12.1)

force an action, like a push or a pull, that causes a change in motion of an object (4.1)

force of friction a force that resists the motion of an object (4.4)

force of gravity mutual force between any two masses (4.2)

fossil fuels the remains of plant life (now coal) or aquatic animal life (now gasoline and natural gas) (6.3)

frame of reference a subset of the physical world defined by an observer in which positions or motions can be discussed or compared (2.1)

framing the process of setting parameters or boundaries to a problem, and organizing them in a way best suited to solve the problem (1.2)

free body diagram a diagram in which all the forces acting on an object are shown acting on a point representing the object (4.4)

frequency number of cycles of periodic motion completed in a unit of time; frequency is the inverse of the period and is measured in s^{-1} or hertz (7.1)

friction a force that resists motion (4.2)

fuel cell a cell that generates electric current directly from the reaction between hydrogen and oxygen without producing thermal energy first (6.3)

fullness an acoustical property of a room characterized by how closely the intensity of the reflected sound compares to the direct sound; opposite to clarity (9.4)

fundamental force one of the four basic forces that governs the behaviour of all matter; see strong nuclear force, weak nuclear force, electromagnetic force, and gravity force (4.5)

fundamental frequency the lowest natural frequency able to produce resonance in a standing wave pattern (7.3)

fundamental mode of vibration the standing wave pattern for a medium vibrating at its fundamental frequency and displaying the fewest number of nodes and antinodes (7.3)

G

Galileo telescope uses a convex objective lens and a concave eyepiece (12.0)

galvanometer a device that detects and quantifies current (15.1)

generator a device that converts mechanical energy into electrical energy (15.0)

generator effect the generation of a current in a coil due to the relative motion of a magnet and a conductor (15.1)

geometric optics the branch of physics that uses the light ray model and rules of geometry to analyze the optical systems (Ch. 10, 11, 12)

geothermal power electrical power derived from the heat of Earth's core (6.3)

gravitational force the fundamental force which operates between masses; the gravitational force has an infinite range (4.2, 4.5)

gravitational potential difference the difference in gravitational potential energy per unit mass between two points, which depends only on the altitude and the acceleration due to gravity (13.1)

gravitational potential energy the potential energy an object has due to its location in a gravitational field; objects at higher altitudes have greater gravitational potential energy than objects at lower altitudes (5.3)

H

harmonic the fundamental frequency and any overtone (8.1)

heat the transfer of thermal energy between two systems due to their different temperatures (6.1)

hertz (Hz) unit used to measure frequency, defined as s^{-1} (7.1)

hyperopia eye condition in which images are brought to a focus beyond the retina because the eyeball is too short; also far-sightedness (12.3)

hypothesis a possible explanation for a question or an observation, which is subject to testing, and verification or falsification (1.1)

I

image a likeness of an object as seen in a mirror or through a lens (10.2)

independent variable the quantity that is deliberately changed or manipulated during an experiment; compare to dependent variable (1.2)

index of refraction the ratio of the speed of light in a vacuum to the speed of light in a specific medium (11.1)

induced current a current produced in a conductor by the motion of the conductor in a magnetic field (15.1)

induced *emf* the potential difference induced in a circuit by a wire moving through a magnetic field or sitting in a changing magnetic field (15.1)

inertia the natural tendency of an object to stay at rest or uniform motion in the absence of outside forces; proportional to an object's mass (4.1)

inertial frame of reference a frame of reference in which the law of inertia is valid; it is is a non-accelerating frame of reference (4.3)

infrasonic sound frequencies lower than 20 Hz (8.2)

inner ear the part of the ear that transforms mechanical movement into electrical impulses that travel to the brain for interpretation (9.1)

in phase the periodic motion of two individual systems vibrating with the same frequency and always in the same stage of the cycle (7.1)

instantaneous acceleration the acceleration of an object at a particular moment in time (2.4)

instantaneous velocity the velocity of an object at a particular instant in time (2.3)

insulator a material that does not allow electric charges to move easily (13.1)

interaction the behaviour of objects as a result of forces (4.2)

interference of waves when waves meet they add algebraically (7.3, 8.3)

internal resistance the resistance inside a battery or power supply (13.4)

intimacy an acoustical property of a room characterized by short reverberation times; small performance halls are considered more intimate than large halls. (9.4)

isogonic lines lines on a map having constant magnetic declination (14.1)

J

joule (J) the SI unit of energy or work; equivalent to applying one newton of force on an object over a distance of one metre (5.1)

K

kelvin (K) the SI unit of temperature; equivalent to one degree on the Celsius scale (6.1)

Kepler telescope uses a convex objective lens and a convex eye piece (12.0)

kilowatt-hour the energy transformed by a power output of 1000 W for one hour; equivalent to 3.6×10^6 J (13.5)

kinematics the study of the motions of bodies without reference to mass or force; the study of *how* objects move in terms of displacement, velocity and acceleration (2.5, 4.1)

kinetic energy the energy of an object due to its motion (5.1, 5.2)

kinetic frictional force a frictional force that acts to slow the motion of an object; measured as the force required to just keep an object sliding over another object (4.2)

kinetic molecular theory all matter is composed of particles that are always in motion (6.1)

L

latent heat of fusion the energy required to melt an amount of mass of a substance (6.1)

latent heat of vaporization the energy required to transform an amount of mass of a substance from the liquid state into a gaseous state (6.1)

lateral displacement the shifting of a light ray to one side, while maintaining the same direction, when it passes through a pane of glass with parallel sides (11.3)

law of conservation of energy the total energy of an isolated system remains constant; energy may be converted from one form to another, but the total energy does not change (5.4)

law of conservation of mechanical energy the total mechanical energy (kinetic plus gravitational potential) of a system always remains constant if work is done by conservative forces (5.4)

law of reflection the angle of incidence of a light ray on any surface is equal to the angle of reflection (both angles are measured with respect to the normal to the surface) (10.1)

law of refraction for any two media, the product of the index of refraction of the incident medium and the sine of the angle of incidence is the same as the product of the index of refraction of the refracting medium and the sine of the angle of refraction (11.2)

law of gravitation a gravitational force exists between all massive objects (1.1)

law of inertia an object remains at rest or continues in straight-line motion unless acted on by an outside force; also known as Newton's First Law (4.3)

lens-maker's equation relates the focal length of a lens to the index of refraction of the lens material and the radii of curvature of the two lens surfaces (12.1)

Lenz's law the direction of the force the magnetic field exerts on the induced current opposes the direction of the motion of the conductor (15.1, 15.2)

light ray an imaginary line that extends from a wave source and indicates the direction of the wave; a ray is perpendicular to a wavefront (10.1)

light ray model a model for finding the image of an object by using light rays to indicate the path that light travels (10.2)

line resistance the internal resistance in a transmission line, due to the material itself (15.3)

lines of force an imaginary line in a magnetic field whose direction indicates the direction of the magnetic field (14.2)

linear propagation of light the principle which asserts that in a uniform medium, light always travels in a straight line (10.1)

liveness an acoustical property of a room directly related to the reverberation time; rooms with longer reverberation times are more "live" (9.4)

loads devices in an electric circuit that receive power and convert electric energy to another form of energy (13.2)

longitudinal wave a wave in which the particles of a medium vibrate parallel to the direction of motion of the wave; for example, sound waves (7.2)

loudness the perceived strength of a sound (8.1)

M

Mach number ratio of the speed of an object to the speed of sound (9.2)

magnetic damping the use of induced magnetic fields to slow down the motion of a conductor moving in a magnetic field (15.2)

magnetic dip the angle that a magnetized needle makes with the horizontal direction when placed in Earth's magnetic field (14.1)

magnetic declination the degree to which a compass needle points away from true north (14.1)

magnetic dipole another name for a magnet that always has two poles such as a bar magnet (14.1)

magnetic domain small region in iron containing material in which individual "magnets" on the atomic level, are all aligned in the same direction (14.1)

magnetic field region of space that will exert a force on a moving charge or magnetic field that enters that space, a vector quantity (14.2)

magnetic field strength the quotient of the force on a charge and charge, Q, and the velocity, v, of the moving charge at a point in the magnetic field (14.2)

magnetic induction the process by which an object becomes magnetized by a magnetic field (14.1)

magnetic monopole a theoretical magnet, never observed or created in the lab, which contains only a single pole (either north or south) (14.3)

magnetosphere the entirety of the magnetic field surrounding Earth (14.2)

magnification the ratio of the size of the image to the size of the object for a mirror or lens (12.3)

magnification equation an equation that relates the quotient of the object height and image height to the quotient of the object distance and image distance (10.3)

mass the quantity of matter an object contains (4.1, 4.2)

mechanical energy the sum of the kinetic and potential energy (5.1)

mechanical wave a wave that travels through a medium as a disturbance in that medium (7.2)

mechanics the branch of physics comprising kinematics and dynamics; simply, the how and the why of simple motion (4.1)

medium a substance, such as air or water or a solid, through which a wave disturbance travels (7.2)

middle ear the part of the ear that is responsible for transforming energy of sound waves into mechanical vibrations that can be transmitted to the inner ear (9.1)

mirage a virtual image that occurs naturally when particular atmospheric conditions cause a much greater amount of refraction of light than usual (11.3)

mirror/lens equation an equation that relates the focal length, object distance, and image distance (10.3)

model a representation of a theory (1.1)

model problem presents a specific physics problem and its solution, using a step-by-step approach (1.2)

motor effect the force exerted by a magnet on (the magnetic field of) a current-carrying conductor which drives electric motors (14.4)

musical instrument an object that can be used to create sounds through vibration of one or more of its parts; classified as brass, woodwind, string, or percussion (9.3)

myopia an eye condition in which images are brought to a focus in front of the retina because the eyeball is too long; also called near-sightedness (12.3)

N

nanotechnology the technology of building mechanical devices from single atoms (1.0)

natural frequency the lowest resonant frequency an object undergoing periodic motion (7.1)

net force the vector sum of all forces acting on an object (4.4)

newton the unit of force required to accelerate 1 kilogram of mass at a rate of 1.0 m/s^2 (4.3)

Newtonian mechanics the study of forces and motions using Newton's laws of motion for macroscopic objects (4.3)

Newton's laws of motion three fundamental laws of motion which are the basis of Newtonian mechanics (4.3)

nodal line a stationary line in a medium caused by destructive interference of individual waves (7.4)

node stationary points in a medium produced by destructive interference of two waves travelling in opposite directions (7.3)

noise mixture of sound frequencies with no recognizable relationship to one another (8.4)

non-conservative force a force that does work on an object in such a way that the amount of work done is dependent on the path taken (5.4)

non-contact forces forces that act even though objects are separated by a distance, such as magnets (4.2)

non-inertial frame of reference an accelerating frame of reference (4.3)

non-linear or non-ohmic resistance devices or materials that do not obey Ohm's law (13.3)

non-uniform acceleration acceleration that is changing with time (2.4)

non-uniform motion the velocity is changing, either in magnitude or in direction, or both (2.3)

normal force a force that acts in a direction perpendicular to the common contact surface between two objects (4.2)

normal line a line perpendicular to a surface (10.1)

north-seeking pole the end of a magnet that points toward the north; commonly known as the north pole (14.1)

nuclear power power produced by the process of splitting extremely large atoms such as uranium into two or more pieces (6.3)

O

object in geometric optics, anything that is a source of light (10.2)

objective lens the lens in an optical instrument that lies nearest the object viewed (12.0)

observation information gathered by the senses (1.1)

Oersted effect an electric current can affect the orientation of a compass needle, just as a permanent magnet can (14.3)

ohm the unit of electric resistance that will allow one ampere of current to move through the resistor when a potential difference of one volt is applied across the resistor, $1\ \Omega = 1\text{V}/1\text{A}$ (13.3)

Ohm's law the law the relates electric resistance to potential different and current (13.3)

open air column an air column that is open at both ends (8.4)

open circuit an incomplete circuit, in which current is unable to flow (13.2)

optical fibre a very fine strand of glass; when light shines into one end of an optical fibre, total internal reflection causes the energy to be confined within the fibre (11.4)

optically dense a refractive medium in which the speed of light is low in comparison to the speed of light in other media (11.1)

ossicles tiny bones, malleus, incus, and stapes, (commonly the hammer, anvil, and stirrup) in the middle ear that work together to amplify soft sounds entering the ear and to protect against excessively loud sounds (9.1)

outer ear the part of the ear that captures and focuses sound waves; composed of the external ear and auditory canal (9.1)

out of phase the periodic motion of two individual systems vibrating with the same frequency is said to be out of phase if they both don't reach the same amplitude at the same instant (7.1)

oval window the membrane-covered opening into the inner ear that transmits mechanical vibrations from the ossicles into longitudinal waves in the fluid of the cochlea (9.1)

overtone all natural frequencies higher than the fundamental frequency in a standing wave pattern (7.3)

P

parabola a geometrical figure formed by slicing a cone with a plane that is parallel to the axis of the cone (10.3)

parabolic reflector a mirror that focuses all the parallel rays of incident light at the focal point (10.3)

parallel a connection in a circuit in which there is more than one path for the current to follow (13.2, 13.4)

paramagnetic a material, whose magnets are initially randomly oriented, which becomes weakly magnetized in the same direction as an applied field (14.2)

paraxial ray a light ray that is close to the principal axis (12.1)

partial reflection and refraction phenomenon in which some of the energy light rays travelling from one medium into another is reflected and some of the energy is refracted at the interface between the media (11.3)

percent deviation a description of the accuracy of a measured value as compared to a theoretical value; calculated as (experimental value – theoretical value)/theoretical value times 100% (Skill Set 1)

percent difference a description of the precision of a set of observations; calculated as (maximum value – minimum value)/(average value of data) times 100% (Skill Set 1)

period the time required for an object to complete one cycle of its repeated pattern of motion (7.1)

periodic motion the motion of an object in a repeated pattern over regular time intervals (7.1)

permanent magnet a magnet that maintains its magnetic properties when removed from an external magnetic field (14.1)

permeability a number which characterizes a material's tendency to become magnetized (is permeable to magnetic lined of force) (14.2)

phase change the change in an object's state of matter, for example, from solid to liquid or liquid to gas (6.1)

phase difference the angular difference between two systems in periodic motion that are not in phase (7.1)

photovoltaic cells solar cells composed of semi-conductors such as silicon, that convert light energy directly into electric energy (6.3)

physics the study of the relationships between matter and energy (1.1)

pitch an attribute of a sound that determines its position in a musical scale; pitch is measured in frequency (8.1)

place theory of hearing the theory that suggests that the location of the hair cells on the basilar membrane detect a specific range of frequencies of sound (9.1)

plane mirror a flat, polished surface that reflects light (10.2)

plano-concave a lens in which one surface is flat and the other curves inwards (12.1)

plano-convex a lens in which one surface is flat and the other surface curves outwards (12.1)

point of divergence point from which light rays diverge (10.3, 12.2)

position vector a vector which points from the origin of a coordinate system to the location of an object at a particular instant in time (2.2)

potential difference the difference in potential the potential energy per unit of mass, charge, etc, of an object due to its position or condition

potential energy energy stored by an object (5.1, 5.3)

power the rate at which work is done, measured in watts (W), or joules per second; also defined as the rate at which energy is transferred or transformed (6.2)

power output the rate at which an appliance can transform electric energy into a desired form such as light, heat, or sound (13.5)

power supply a device such as a cell, battery, or generator which supplies electrical energy to a circuit (13.2)

precision describes the exactness and repeatability of a value or set of values (Skill Set 1)

prediction a statement of what you would expect to observe in an experiment, based on the hypothesis (1.1)

presbyopia an eye condition equivalent to far-sightedness due to the lens losing flexibility which occurs with advanced age (12.3)

primary coil the coil in a transformer that is connected to the initial fluctuating or alternating current (i.e., the power supply) (15.3)

principal axis a straight line that passes through the vertex, the centre of curvature and the mirror or lens (10.3, 12.1)

principal focus the point on the principal axis which light rays parallel to the principle axis converge on or appear to diverge from; also called the principal focal point (10.3, 12.1)

principle of reversibility of light when a light ray is reversed, it travels back along its original path (11.2)

principle of superposition a combined or resultant wave is the sum of its component waves (7.3)

prism a transparent object used for refracting, dispersing, or reflecting light rays (11.3)

pure a description of the quality of a sound, such as that of a flute or whistle; pure sounds typically have few overtones; compare to rich (8.1)

Q

qualitative observation a verbal description of an object or phenomena; for example, "the book is heavy" (1.1)

quality an attribute of a sound used to distinguish between sounds having the same fundamental frequency but a different set of overtones (8.1)

quantitative observation a numerical description of an object or phenomena; for example, "the book has a mass of 5 kg"; quantitative observations typically involve measurements of a particular quantity (1.1)

quantum mechanics a branch of modern physics that deals with matter and energy on atomic scales (4.5)

quintessence a fifth substance that celestial objects were made of, according to the Greek scholar, Aristotle (1.1)

R

radius of curvature any straight line drawn from the centre of curvature of a mirror or lens to the curved surface (10.3)

rainbow an arc of colours of the visible spectrum appearing opposite the sun, caused by reflection, refraction, and dispersion of the sun's rays as they pass through drops of rain (11.5)

random error results from small variations in measurements due only to chance (Skill Set 1)

rarefaction a region of lower air pressure compared to the surrounding medium; longitudinal waves have both compressions and rarefactions (8.1)

ray a line drawn perpendicular to the wavefronts of a wave (7.4)

real image an optical image that would appear on a screen if a screen were placed at the image location (10.2)

recombination the process whereby a dispersed spectrum of light can be put back together into white light (11.5)

rectified current an alternating current that is transformed into a pulsating direct current (15.1)

refraction the change in the speed of a wave due when it travels from one medium to another (7.4, 11.1)

refracting telescope a telescope which uses only lenses and no mirrors to create an image (12.3)

regular reflection reflection in which the reflected light rays are parallel to one another, as from the surface of a mirror (10.1)

relative velocity a velocity relative to a frame of reference, such as an air current, that itself is moving with a velocity relative to another frame of reference, such as the ground (3.2)

relative uncertainty the ratio of the estimated uncertainty to the actual measured value, written as a percentage (Skill Set 1)

resistance in electricity, the resistance to the flow of electric current in a circuit; similar to frictional resistance in motion (13.3)

resistivity a property of a material that describes the ease with which it permits the flow of electric current (13.3)

resolved vectors components of a vector that are at right angles to each other; the components lie parallel to the axes of the coordinate system (3.2)

resonance phenomena that occurs when energy is added to a vibrating system at the same frequency as its natural frequency (7.1)

resonance length the specific lengths of a column at which resonance occurs, typically measured in fractions of wavelength (8.4)

resonant cavity an open or closed air column in which a standing wave pattern and varied sounds can be created (9.1)

rest position the position of an object, such as a simple pendulum or a mass on a spring, when it is allowed to hang freely and is not moving (7.1)

resultant vector a vector obtained by adding or subtracting two or more vectors (3.1)

resultant wave a wave produced by combining or superimposing two or more individual waves (7.3)

retroreflector an optical device used to reflect light directly back parallel to its original path (11.4)

reverberation time the time it takes for all echoes in a room to fade away and become inaudible (9.4)

rich a description of the quality of a sound, such as that of a cello or organ; rich sounds typically have many overtones; compare to pure (8.1)

right-hand rules the rules which help to visualize the directions of vectors describing properties involved in electromagnetism by using the fingers and thumb of your right hand. (14.3)

S

scalar a physical quantity that has only a magnitude or size (2.2)

scale diagram a diagram in which the relative sizes and directions of objects or vectors are preserved with respect to a particular coordinate system (4.3)

scientific method a procedure used to understand the natural and physical world; it consists of several steps: 1) observations of phenomena; 2) formulating a hypothesis that describes these phenomena and is consistent with present knowledge; 3) testing the hypothesis by making new observations, analyzing experiments, and using it to predict new phenomena; 4) accepting, modifying, or rejecting the hypothesis (1.1)

science the process of creating a system of principles and laws that describe phenomena in the natural and physical world (1.1)

scientific law a principle that has been thoroughly tested and observed that scientists are convinced that it will always be true (1.1)

second law of thermodynamics a process of transferring heat and doing mechanical work in which some thermal energy will always leave the system without doing work; thermal energy is always transferred from an object at a higher temperature to an object at a lower temperature (6.2)

secondary axis any line other than the vertical axis that passes through the intersection of the vertical axis and the principal axis (12.1)

secondary coil the coil in a transformer in which currents are induced (15.3)

secondary focus a point on the secondary axis which parallel light rays converge on or appear to diverge from; also called the secondary focal point (12.1)

sensorineural hearing loss due to damage to the hair cells within the cochlea (sensori) or to the auditory nerve and auditory receptors within the brain (neural) (9.1)

series a connection in a circuit in which there is only one path for the current to follow (13.2, 13.4)

slip-ring commutator a circular conductor attached to the coil of a motor or AC generator that is in contact with brushes that allows the continuous electric connection to the rest of the circuit (15.1)

Snell's law for any two media, the product of the index of refraction of the incident medium and the sine of the angle of incidence is the same as the product of the index of refraction of the refracting medium and the sine of the angle of refraction (11.2)

solenoid a closely wound helix of wire that acts as a magnet when current runs through the wire (14.3)

sonic boom an acoustic pressure wave caused by an object moving faster than the speed of sound (9.2)

sound intensity level the rate of energy flow across a unit area; measured in an exponential scale in units of bels (B) (8.2)

sound spectrum a plot of intensity versus frequency for the various frequencies that make up a sound (8.4)

source of light anything that has light coming from it, either from reflection or radiation (10.2)

south-seeking pole the end of a magnet that points toward the magnetic pole near the geographic South Pole; commonly known as the south pole of a magnet (14.1)

specific heat capacity the amount of energy that must be added to a substance to raise 1.0 kg of its material by a temperature of 1.0 degree kelvin (6.1)

spectrometer an optical instrument used to measure the precise frequencies or wavelengths produced by a light source (11.5)

speed the distance an object travels divided by the time the object was travelling; speed is a scalar quantity (2.2)

speed of light the speed at which light travels; the speed of light in a vacuum is a fundamental physical constant (11.1)

spherical aberration an optical problem in spherical mirrors and lenses in which parallel rays far from the principal axis are not brought to the same focus as parallel rays close to the principal axis (10.3)

spherical mirror a mirror with the shape of a section sliced from the surface of a sphere; a mirror, either convex or concave, whose surface forms part of a sphere (10.3)

split-ring commutator a device which allows continuous connection of the rotating rotor (or armature) to the rest of the circuit in a motor or generator; used in DC motors and generators to reverse the current direction (14.4, 15.1)

standing wave a stationary wave consisting of nodes and antinodes, formed when two equal travelling waves pass through one another in opposite directions (7.3)

static frictional force a frictional force that acts to keep an object at rest; measured as the force required to start to move an object from rest (4.2)

step-down transformer a transformer that has fewer windings on its secondary coil, and acts to decrease voltages (15.3)

step-up transformer a transformer that has more windings on its secondary coil, and acts to increase voltages (15.3)

strong nuclear force the fundamental force that holds the parts of the nuclear together; the strong nuclear force has a short range (4.5)

super force a theoretical force, thought to exist early in the history of the universe, in which all four of the fundamental forces are unified (4.5)

superconductors materials that at extremely low temperatures conduct electricity with absolutely no resistance (13.3)

systematic error results from bias in observations that won't be reduced by repeating the measurement (Skill Set 1)

T

tangent a line that intersects a curve at only one particular point (2.3)

tectorial membrane in the cochlea, the organ that touches the projections of hair cells and causes them to bend when the basilar membrane vibrates (9.1)

temperature a measure of the average kinetic energy of the atoms or molecules of a substance (6.1)

temporal theory of hearing a theory that suggests that groups of hair cells in the cochlea (in the inner ear) discharge signals in time with the frequency of the incident sound (9.1)

temporary magnet a magnet that loses its magnetic properties when removed from an external magnetic field (14.1)

terminal voltage the potential difference across the poles of a battery (13.4)

tesla (T) unit of magnetic field strength, equivalent to the magnetic field that exerts a force of one newton (1 N) on a one-metre-long (1 m) conductor carrying a current of one ampere (1 A); equivalent to a newton per ampere metre (14.1)

texture an acoustical property of a room which refers to how rapidly reflected sounds from different directions reach a listener (9.4)

theory a collection of ideas and principles, validated by many scientists, that have been demonstrated to describe and predict a natural phenomenon (1.1)

thermal energy the kinetic energy of the particles of a substance due to their constant, random motion (6.1)

thermal equilibrium the state in which the energy transfer between bodies in a system is equal; bodies in thermal equilibrium have the same temperature (6.1)

thermosphere the highest layer of the atmosphere, beginning at approximately 100 km above Earth's surface, where the temperature rises continuously with altitude (6.1)

thin-lens equations the mirror/lens and magnification equations, relating focal length, image distance, and object distance; accurate, in the case of lenses, only if the thickness of the lens is small compared to its diameter (12.1)

tidal power power derived by capturing high tide waters and releasing them through turbines during low tide (6.3)

timbre the difference in quality of sound between two instruments playing the same note; due to the different harmonic structure of the sounds (9.3)

time interval the amount of time that passes between two instants of time (2.1)

torque similar to force but causes a change in the rotation of an object (4.4)

total internal reflection phenomenon in which light incident on the boundary of an optically less-dense medium is not refracted at all but is entirely reflected back from the boundary into the optically more-dense medium; occurs when the angle of incidence is greater than the critical angle (11.4)

transformer a device used to convert power from the high voltages used in transmission to low voltages safe for use in homes; increases or decreases AC voltages with little loss of energy (15.3)

transverse wave a wave in which the particles of a medium vibrate at right angles to the direction of motion; for example, water waves (7.2)

trough the lowest point on a wave (7.2)

U

Ultrasonic sound frequencies higher than 20 000 Hz (8.2)

uniform acceleration acceleration that is constant throughout a particular time interval (2.4)

uniform motion moving at constant velocity (2.3)

universal wave equation the fundamental equation governing the motion of waves that relates the velocity of the wave to its frequency and wavelength (7.2)

V

variable a quantity that may change in an experiment (1.2)

vector a quantity that has a magnitude and a direction; vectors must be defined in terms of a frame of reference (2.2)

vector components parts of a vector that are parallel to the axes of a coordinate system, into which a vector can be resolved; they are scalar quantities (3.3)

vector diagram a diagram, with a coordinate system, in which all quantities are represented by vectors (3.1)

velocity the rate of change of position of an object; a vector quantity (2.2)

vertex the geometric centre of a curved mirror or lens surface (10.3)

vertical axis the axis of the mirror or lens which passes through the vertex and is perpendicular to the principal axis (12.1)

virtual focus a point which light rays appear to converge to or diverge from (10.3)

virtual image an image that can only be seen by looking *into* the mirror or lens that is creating it; virtual images will not appear on a screen when a screen is placed at the apparent image location as light rays do not actually pass through a virtual image (10.2, 12.1)

virtual object an apparent image, not yet formed, used as an object for a second lens; this happens by placing a second lens or mirror in the path of the converging rays of the first lens or mirror, before a real image is formed (12.4)

visible spectrum the range of colours of light that human eyes can see; from long wavelength to short wavelength, the visible spectrum comprises the colours red, orange, yellow, green, blue, indigo, and violet; includes wavelengths from 400 to 700 nm (11.5)

vocal cords two thin folds of muscle and elastic tissue that can be opened and closed to restrict air flow entering and leaving the lungs; oscillations of the vocal chords are responsible for speech (9.1)

volt (V) the SI unit of potential difference and emf (13.1)

voltage the potential difference between two points in a circuit (13.0)

voltaic cell a cell consisting of two different metals, called electrodes, placed in an electrolytic solution in which chemical reactions produce an electric charge on the electrodes (13.1)

voltmeter a device that measures the potential difference across a circuit element (13.2)

W

warmth an acoustical property of a room obtained when the reverberation time for low frequencies is longer than for high frequencies; opposite to brilliance (9.4)

watt (W) a unit of power, equivalent to 1 joule per second (13.5)

wave a disturbance that transfers energy through a medium (7.2)

wave power electrical power derived by harnessing the energy of water waves (6.3)

wave theory of light a theory that proposes that light travels as a wave and has all of the properties of waves (10.1)

wavefront a group of adjacent points in a wave that all have the same phase, usually indicated by a line drawn along the crests of a wave (7.4, 10.1)

wave equation the fundamental equation governing the motion of waves that relates the velocity of the wave to its frequency and wavelength (7.2)

wavelength the shortest distance between any two points in a medium that are in phase; commonly measured from one trough to the next trough, or one crest to the next crest (7.2)

weak nuclear force the fundamental force that causes radioactive decay; the weak force has an extremely short range (4.5)

weight the force that gravity exerts on an object due to its mass (4.2)

work the transfer of mechanical energy; equivalent to a force acting through a distance (5.1)

work-energy theorem the relationship between the work done on an object and the resulting change in any of the object's forms of energy, $W = \Delta E$ (5.2)

work-kinetic energy theorem the relationship between the work done on an object and the resulting change in kinetic energy, $W = \Delta E_k$ (5.2)

Index

The page numbers in **boldface** type indicate the pages where terms are defined. Terms that occur in investigations (*inv*), Model Problems (*MP*), MultiLabs (*ML*), and QuickLabs (*QL*), are also indicated.

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